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# AUTOMATION OF THE COLLECTION AND ANALYSIS OF SCIENTIFIC INFORMATION IN THE PROBLEM OF THE INTERACTION OF THE ATMOSPHERE AND OCEAN

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16. Abstract
This collection contains material from research into the interaction of the atmosphere and the ocean, including both experimental research conducted aboard scientific research vessels, and work of a theoretical nature. A number of articles are devoted to the principles basic for a ship automated system that collects and analyzes oceanological data. The theoretical articles deal with the basic concepts of hydrodynamic models of atmospheric and oceanic circulation.

Abstracts of individual articles are included at the end of the volume.

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# FOREWORD

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The present collection contains material from research into the problem of the interaction of the atmosphere and ocean, including experimental research aboard scientific research vessels and work of a theoretical nature.

The first group of articles is devoted to the principles of the establishment and work of the ship automated system for collection and analysis of scientific information aboard the scientific research vessels of the GUGMS (Main Administration of the Hydrometeorological Service), equipped with computers. Thus, the papers by Ye. P. Borisenkov, O. M. Federov and I. A. Dyubkin discuss the principles which form the basis of the ship automated system known as SIGMA-s and its mathematical foundation.

In the article entitled "The Problem of the Organization of a Coastal Coordinating and Computing Center" are given the fundamental principles of the operation of a coastal coordinating and computing center under automation conditions. Special attention is devoted in this article to the work of the coastal computer center of the AANII (Arctic and Antarctic Scientific Research Institute), which simultaneously performs the functions of generalizing data from Arctic and Antarctic expeditions and from observations at the polar stations.

The articles by O. S. Zudin, B. A. Nelepo and V. A. Stepanyuk describe the algorithms and programs for automated analysis of deep-water hydrological information and the basis for the selection of the interval of discreteness of measurements in a hydrophysical field. The authors touch on several methodological problems involved in making measurements at sea.

The second group of articles deals primarily with theoretical works in which there is a discussion of the basic principles involved in the construction of hydrodynamic models of the circulation of the atmosphere and ocean, as well as methods of obtaining and analyzing hydrometeorological information.

The article by Ye. P. Borisenkov is a description of the small parameter nonadiabatic model of the circulation of the atmosphere, based on the integration of complete equations and taking into account the interaction between the atmosphere and ocean. His next article is a description of the small-parameter model of a stationary

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*Numbers in the margin indicate pagination in the foreign text.

and non-stationary circulation of a baroclinic ocean which is inhomogeneous by depth. Recommendations are given in connection with the integration of the equations obtained by using certain analogs with the integration of equations for atmospheric circulation.

A. P. Nagurnyy presents a simplified method for estimating /4
the heat fluxes on the subjacent surface on the basis of data from a synoptic analysis.

The article by Z. G. Savchenko and V. R. Fuks subjects the behavior of internal gravitational waves to analysis.

The last two articles deal with the results of several experimental research projects. Z. P. Galakhov describes the results of a calculation of the fluxes of outgoing radiation with consideration of cloud cover on the basis of mean monthly data; T. I. Bazlova suggests one possible approach to the solution of the problem of restoration of the moisture profile in the atmosphere with respect to the vertical temperature profile.

The collection is intended for a wide circle of specialists, working on both the theoretical and research level, and in physics of the atmosphere and ocean, as well as the scientific workers, engineers, the members of expeditions aboard scientific research vessels, those interested in the automation of the collection and analysis of ship information. The collection may be valuable to students in senior courses at the university and graduate students specializing in meteorology and oceanology, as well as those working in the operational units of the hydrometeorological service. The collection will also be of some interest to those persons who are concerned with the development of apparatus to be installed aboard scientific research vessels.

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## LIST OF ABBREVIATIONS

AANII--Arctic and Antarctic Scientific Research Institute

AIK----Autonomous Memory Complex

AIS----Automated Data System

AKOI---Automatic System for Data Processing

AM-----Analog Computer

AMTs---Antarctic Meteriological Center

ATsP---Analog-Digital Computer

ATsPU--Alphanumeric Printer

BKVT---Coastal Coordinating Computer Center

CCC----Coastal Computer Center

CRT----Cathode Ray Tube

DARMS--Drifting Automatic Radiometeorological Station

DNI----Permanent Information Medium

GMTs---Hydrometeriological Center

GUGMS--Main Administration of the Hydrometeorological Service

ID-----Input Device

IIK----Data Measuring Complex

IPS----Information Retrieval System

IPYa---Information Retrieval Language

KIOSK--Complex for Information Exchange with Ship Complex

MC-----Hydrometeorological Measuring Complex

MOZU---Internal Magnetic Storage

MTK-2--Baudot (Telegraphic) Code

NIR----Scientific Research Work

NMI----Magnetic Tape Storage

OSAK---Devices for Exchanging Information Between Ship and Autonomous (Automated) Complexes

PGSAP--Program for Global Studies of Atmospheric Processes

Poisk-OK--Soviet Information Retrieval System based on Address of Microcopies in Computer Memory

RGMTs--Regional Hydrometeorological Center

SAE----Soviet Antarctic Expedition

SAM----Punched Card Machine

SCC----Ship Computer Center

SIA----Ship Measuring Device

SIF----Information Reference Bank

SIGMA-s-System, Information, Hydrometeorological Automated Ships

SIUVK--System for Interconnecting all Hydrometeorological Complexes

SP-----Monitoring Station

SRV----Scientific Research Vessel

TGM-3--Thermohydrobarometer

TGMTs--Territorial Hydrometeorological Center

TM-----Thermometer

VINITI-All-Union Institute of Scientific and Technical Information

WWW----World Weather Watch

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# AUTOMATED SYSTEM FOR MEASUREMENT, COLLECTION AND PROCESSING OF HYDROMETEOROLOGICAL DATA ABOARD SCIENTIFIC RESEARCH VESSELS OF THE GUGMS* (SIGMA-s)

/5

Ye. P. Borisenkov
and
O. M. Fedorov

At the present time, there has been a significant increase in interest in studying the world ocean, not only in the U.S.S.R. but in many other countries as well (U.S.A., Great Britain, France, Japan, Canada). An important role in this connection is played by the large scientific research vessels (SRV) which are equipped with all necessary technical equipment for measurement, collection and analysis of hydrometeorological data. The study of the oceans is of interest to a great many different disciplines, with particular emphasis on the solution of its problems, and in the final analysis this is reflected in the composition of the ship measurement complexes, planning of expeditions, and so on. Recently, a tendency has been noted toward the development of partially or completely automated ship measurement and information complexes for the collection, analysis and utilization of scientific data. The ship automated systems, intended for use aboard the scientific research vessels of the hydrometeorological service, also have some specific features which reflect the problems which the service faces.

As we know, the principal task of the hydrometeorological service is the development of reliable methods of hydrometeorological forecasting, especially long-range forecasting, and the prompt provision of necessary hydrometeorological information to interested consumers on a global scale. This has been reflected in the plans for carrying out such large international projects as the World Weather Watch (WWW) and the program for global studies of atmospheric processes (PGSAP). In these plans, particular emphasis is placed on the study of the interaction between the atmosphere and the ocean, and on extracting information from the least observed regions of the ocean.

Large scientific research vessels (of the "Professor Vize" type), equipped with computers and modern measuring apparatus, are floating institutes in the true sense of the word; they are capable of taking part in the performance of complex studies of large scale scientific and economic problems, and in many cases of solving independent problems. Obviously, in addition to the problems related to the

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* Translator's Note. GUGMS = Main Administration of the Hydrometeorological Service of the USSR.

solution of forecasting difficulties, the SRV must carry out a great deal of work in the comprehensive study of the depths of the oceans and the atmosphere above them.

However, the tasks of the hydrometeorological service and the weather forecast in particular, place particular emphasis on the problem of the study of the interaction between the gaseous and liquid envelopes of the Earth, which is taken into account in the development of their measurement equipment and programs for the operation of the SRV of the GUGMS. /6

Among the scientific programs which it is proposed to solve by means of scientific research vessels the following are the most important [12]:

(1) Study of the physics of the interaction of the atmosphere and ocean in the boundary layers;

(2) Study of the thermodynamic processes throughout the entire depth of the ocean, with determination of the physics of the formation and characteristics of boundary layers;

(3) Study of the processes in the atmosphere above the ocean, including the formation and characteristics of the boundary layer of the atmosphere, fields of humidity and cloud cover above the ocean;

(4) Study of the way that the radiant energy from the sun and the radiation field react with the ocean and atmosphere above it (keeping in mind that the ocean is the principal source of formation of humidity and cloud cover fields which are responsible in the main for the absorption of short wave and long wave radiation);

(5) Determination of the degree and influence of the ocean on the atmosphere and its reverse action on the ocean in specific geographical regions and at different seasons.

The measuring instruments which exist at the present time are unable to solve all of the problems listed above. This raises the necessity for developing the necessary instruments on the basis of well-founded technical requirements to be placed on them. However, the apparatus now aboard research vessels can provide such a large quantity of information that it cannot be effectively utilized if it must be analyzed manually. A scientific research vessel of the "Professor Vize" type alone will collect up to $10^8$ bits of data in the course of a 100-day expedition at sea. Equipping the vessels with equipment for studying the micro structure of the hydrometeorological fields in the ocean or atmosphere above it increases the volume of information gathered to $10^9$-$10^{10}$ bits.

Computers aboard the large research vessels can ease the situation somewhat but do not change the basic situation, inasmuch as the principal problem of automation of the analysis of any information is that the methods of recording the data do not allow it to be stored immediately in a computer [5, 7]. These factors also make it necessary to develop as soon as possible automated systems of equipment to be used aboard scientific research vessels for the collection, transmission and analysis of hydrometeorological data.

At the present time, GUGMS vessels of the "Professor Vize" type have seven hydrometeorological measuring complexes (MC): /7

(1) A hydrological system, intended for studying hydrological fields of the ocean from the surface down to the bottom;

(2) A hydrochemical system for chemical study of the ocean from the surface to the bottom;

(3) Meteoactinometric system for measuring and assessing meteorological and actinometric data;

(4) Aerological system, for studying the free atmosphere from sea level to altitudes of 35-40 kilometers;

(5) The radiochemical system, for determining the concentration of radioactive isotopes in the atmosphere;

(6) The rocket method, for sounding the upper layers of the atmosphere;

(7) The satellite system, for receiving data from meteorological satellites that use the direct transmission system.

In addition, a number of these measurement systems have been developed in the course of specific voyages for solving problems of a limited nature. The ship computer center (SCC) which consists of a "Minsk-22" computer, is intended for analyzing the results of research and solution of routine problems.

Without going into detail about the parameters which are measured, or the ranges, accuracy, space-time discreteness, methods of measurement and recording for all of the systems, let us establish a classification of the types of information that will be based on the characteristics of the observations and the methods of recording:

(1) Visual observations and manual recording of results (logs and notebooks);

(2) Instrument observations in the laboratory and manual recording of the results;

(3) Instrument observations in situ and manual recording of the results;

(4) Instrument observations in situ and automatic recording of the results in a form which is unsuited for inputting into a computer input (graphs, printout, photography);

(5) Instrument observations in situ and automatic recording of the results on a technical information medium in a machine code or direct transmission of the data to the computer memory.

The latter form of recordinginformation is by far the most preferable for subsequent analysis in a computer. At the present time, the vessels of the GUGMS are carrying out all of the observations listed above but only the MC rocket satisfies the requirements of the latter type. The system for the collection and analysis of hydrometeorological data aboard scientific research vessels have the following characteristics:

(1) The collection subsystem consists of a great many instruments and measuring devices which are extremely diverse in terms of the physical principles of measurements on which they are based and the methods of recording;

(2) The electrical methods of measuring hydrometeorological parameters employed in the measurements far from exhaust their possibilities, since the recording of the measured values is carried out manually (entries in logs of a specific kind), and it is only in certain cases that recording is extended to the automatic plotting of graphs; /8

(3) None of the recording methods (with the exception of recording in the MC rocket) allows computer analysis of the data without preliminary tedious preparation, which leads to a minimum efficiency of computer use.

With the existing measurement system, the scientific research vessels of the GUGMS are not yet being used sufficiently for solving the problems of the interaction of the atmosphere and the ocean. At the present time, due to the lack of measuring instruments, almost no work is being done on such tasks as the following:

(a) Study of turbulence in the layer of the atmosphere nearest the water;

(b) Study of turbulence in the active layer of the ocean;

(c) Study of the pattern of spatial variation of the physical and chemical fields of the ocean;

(d) Investigation at a single point of the time changes in the physical and chemical parameters of the ocean for a prolonged period;

(e) Study of the spectral characteristics of the transparency of the atmosphere above the ocean, measurement of the incoming-outgoing radiation on the short wave, visible, infrared, submillimeter and microwave ranges;

(f) Comparison of the variations in the fields of physical parameters of the atmosphere and ocean and the study of their interaction.

During the last decade, work has been conducted both in the Soviet Union and abroad on the development of ship automated information systems. Several of them have been built and used.[1]

In order to describe the general characteristics, we will discuss several systems used in the U.S.A.. The ODRS system, which was installed in 1963 aboard the research vessel "Chaine", is designed for working on a real-time scale. It consists of an IBM-1710 control computer, an analog-code converter block, an external memory device and a system of measuring devices. The system provides for manual input of data on the ship's position, the depth of the ocean, observation time, and so on. The computer automatically receives data from the log, gyrocompass, gravimeter, magnetometer, echo sounder and hydrological sensors.

The SSS system is intended for the collection and recording of oceanographic data with the ship traveling at speeds up to 15 knots and on drifting stations. It includes a set of measuring instruments, a distributor block, devices for analog-digital conversion, input and output devices, recorders of raw and analyzed information, and a control panel. In addition to the above, the DATAC, "PRODAC-510" and other systems are used in the United States. They are also intended for automation of the collection, recording and initial processing of oceanographic data in particular. Similar problems are solved by automated data systems in Canada and Japan. /9

One of the first automated systems for collection and analysis of hydrological information in the U.S.S.R. was developed at the Marine Hydrophysical Institute of the Academy of Sciences of the Ukrainian S.S.R. It consists of three main parts:

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1. A detailed survey of the systems will be found in [3, 11].

1. A subsystem of measurement devices, including onboard MC, outboard sounding devices and autonomous buoy MC. The measuring systems allow the collection and transmission of data to a subsystem for initial processing.

2. The subsystem for the initial processing of data and the operative control of the subsystem for measurement devices (based on a computer).

3. A coastal subsystem for the analysis and documentation of outgoing data, planning and control of expeditions (developed on the basis of a coastal computer center, CCC).

The experience of the Marine Hydrophysical Institute of the Academy of Sciences of the Ukrainian S.S.R. in the development of automated ship information hydrological systems allows the following conclusions to be drawn:

1. The system consists of measuring and data-computer systems of apparatus that carry out certain functions in the process of measurment, collection and analysis of data;

2. The systems are linked by a single unified digital representation of data at the output;

3. In the course of the experiment the computer is used for primary analysis and information for the purpose of checking its operations;

4. The final analysis of data is carried out at the CCC, which combines and documents the data that have been collected and uses this as the basis for planning and controlling marine expeditions.

More details on the problem of automation of marine studies and their solution can be found in [4, 5, 6, 9].

It is clear from this brief survey that individual principles in the development of ship automated systems, even on the scale of a single country, are handled in different ways. This is due primarily to the specific nature of the problems to be solved, the makeup of the measuring systems and their role in the process of scientific evaluation of the data. However, certain principles which form the basis of automated systems allow any other automated measuring systems to be connected to them.

The staff working on the automated system for use aboard the GUGMS vessels concluded, in the course of its preliminary scientific and methodological work, that it was necessary to try to build a single automated system for the collection and analysis of data on the scale of a single vessel equipped with a computer, in view of the compactness of shipboard communication lines.

However, the development of individual automated measuring systems, from which the members of the expedition can transmit a technical carrier with data for analysis at the SCC (Ship Computer Center), will not completely solve the problem of automation of marine studies. The development of a single ship automated information system with internal feedback will make it possible not only to increase the feasibility of the collection and analysis of scientific data, but also will optimize the processes of controlling these studies on the basis of a broad introduction of machine methods of analyzing the results [1]. /10

Inasmuch as the automated hydrometeorological system is being developed under conditions when the actual recording of the data is not provided in a form convenient for machine handling, it is planned to to ahead with its development in two stages.

The first is the automation of information collection, i.e., the development of automated measuring systems, from whose output the researcher can gain information on the technical carrier in a form which is convenient for machine processing, without taking into account other convenient methods of recording and the development of the necessary programs for machine analysis of this data. Such automated equipment will be used aboard all the research vessels, even those which are not equipped with a computer. The data which is obtained from the automated measuring system aboard the ships that are not equipped with computers will be processed at a coastal computer center.

The second approach is a marriage of the automated measuring devices withthe computer through devices for interfacing and the development of a software system for the automated information system based on programs for analysis of the information, also including a control program. This stage of automation is only possible aboard vessels that are equipped with computers.

Let us discuss briefly the fundamentals of the construction of measuring and data complexes for ships automated systems known as SIGMA-s, intended for the scientific research vessels of GUGMS. Let us examine first of all the name of this system: In Russian, the letters SIGMA-s represent the words "System, information, hydrometeorological, automated, ship's". The measuring apparatus of the SIGMA-s, in accordance with the specific nature of its purpose, is composed of the following units: meteoactinometric, aerological, study of small-scale interaction of atmosphere and ocean, vertical sounding of the atmosphere by optical and radiometric methods, obtaining information from meteorological earth satellites, hydrological rocket, navigational systems of apparatus for linking the ship's automated systems and the SCC, the ship computer center.

The measuring systems of the SIGMA-s are divided into two types according to procedure:

The systems for carrying out standard observations, such as measured parameters, range, accuracy, and discreteness both in space and time, are based on standard methods that are employed aboard the research vessels of GUGMS at the present time.

The systems for carrying out scientific research in accordance with specifically stated problems. To develop a method of investigation, a short time is required to obtain a deliberate excess of data so that it can be used as a basis for determining the optimum frequency of observations and other characteristics. In this case, the requirements imposed on the MC (Measuring Complex) designated for observations can be made more specific. /11

The technical task for the development of automated measurement and information handling apparatus with subsequent incorporation in the SIGMA-s boils down to the following:

1. Introduction of electrical measurement of physical parameters;

2. Unification of the output signals, both digital and analog;

3. All data to be recorded is recorded in a technical carrier in a form which is convenient for direct input into the computer;

4. In addition to the development of new measurement systems, modernization of the existing ones;

5. Maximum unification of the block diagrams of the devices for convenience of use and modifications.

There are three ways to automate the collection and analysis of scientific data onboard ships:

1. To equip the scientific research vessels with computers and measurement systems in which the recording of data is carried out with a technical carrier in a machine code. The information is fed into the computer from the technical carrier, received from the measurement systems through an input device (ID) on the computer.

2. Combination of the MC and the first version of the computer with addition of central controlled devices and a unit time block to the automated system. However, differences in the technical

solutions adapted when constructing the measuring devices, the devices for coupling the measuring systems and the computer, will require the use of matching devices to combine the systems. This will lead to unnecessary complexity of the system as a whole. When it is necessary to modify individual measuring systems or to add new ones to the system, tedious experimental design changes will have to be carried out.

3. To develop for ship automated information systems a unified measuring and information apparatus. To connect all the measuring systems with the ship computer and with each other if necessary. The need for a single form of representation of the data is retained. In this case, the system will be more unified: the modules and assemblies of the apparatus will be built on the basis of a single system of logical elements which will facilitate its use and will make it possible to build typical blocks and assemblies for the realization of the working algorithms of the various measuring systems. It is also possible to achieve a unification of the algorithms for the function of the measuring devices. Standardization of /12
the blocks and assemblies will allow standard monitoring of the function of the apparatus which will in turn facilitate the detection and elimination of problems, and will allow individual MS to be reconstructed without additional research and development expenditures and to add new ones.

Experience in automation of the collection and analysis of hydrometeorological data shows that the measuring devices must employ electrical measuring converters in one of the initial branches of the measuring circuit, and then there must be an analog-digital conversion of the electrical signals into machine code. All the conditions of the fifth type of observation are satisfied. However, at the present time there are no realistic possibilities of translation from the first to the second or from the second to the fifth for certain types of observations (for example, for observations of cloud cover or weather phenomena, or even for hydrochemical observations). A similar opinion has already been expressed in [10]. Thus, the absolutization of the requirement for the observations of the fifth kind will postpone the automation of collection and analysis of hydrometeorological data for an unspecified period of time.

Therefore, the block diagram of the MS must combine the fifth type of observation with manual input of certain parameters whose automatic measurement is impossible. With an insignificant rate of input of hydrometeorological data (in comparison with the high speed of a computer) and the need for accumulating a significant volume of observations for analysis, it is not advantageous to use hydrometeorological information for input into a computer on a real-time scale. It does make sense to combine the measuring system with the computer through a device for buffer storage of information. Taking into account the necessity of formation of complex assemblies from diverse hydrometeorological data, and at the same time suppressing the information which has a random statistical nature, it is necessary to provide in the apparatus, for coupling of the measurements and the computer, analysis blocks and primary analysis of information. All of the more complicated forms of analysis of the data gathered in the course of the experiment, extending to its complex evaluation and the preparation of the results for documentation, are carried out by the ship's computer center.

The information cybernetics system of individual automated systems and the SIGMA-s as a whole, as well as the cybernetic system of control of the experiment, should advantageously be constructed along the following guidelines. The information cybernetic system of the MC has two versions: for a complex which is capable of operating without an output to a computer and for a complex which is connected to a computer.

In the first case, the output of the measuring system gives to the user data which are suitable for use in practical work. For this purpose, the MC must carry out some data processing for the purpose of converting it into natural physical values. The information cybernetics system of the MC for the first version must correspond to the system shown in Figure 1 [1].

In any case, it is advantageous to carry out the analysis of the information coming from the MC on the ship's computer, so that the information cybernetics system can be simplified by excluding all of the processing blocks and their connections. All that is left is a flow of unprocessed information. /13

The information cybernetics system shown in Fig. 1 is similar in all respects to the system for combining the measurement devices with the ship's computer (in the following, it will be referred to as KIOSK--the Russian letters stand for Complex for Information Exchange with Ship Complexes). The data on entering the KIOSK from the MC may be stored in the computer without being accumulated in a buffer memory. If it is necessary to formulate a mass of diverse information for input into the computer, the data which enters the KIOSK undergoes a sorting process. When it is necessary to compress the information for input into the computer, the data arrays that result pass through a statistical analysis.

On the basis of the principles outlined above and in accordance

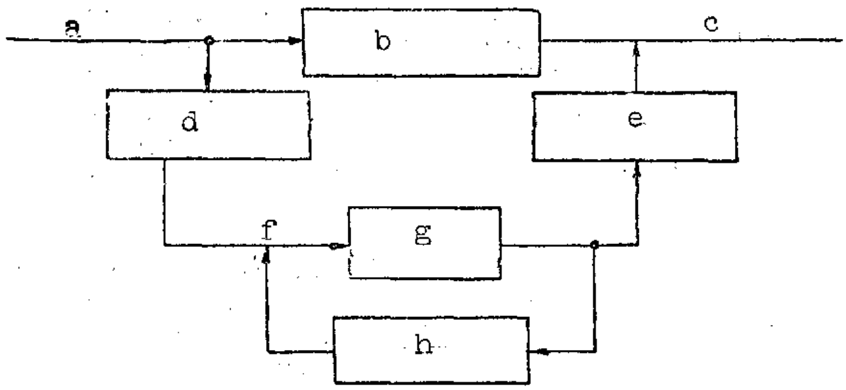


Fig. 1. General informational cybernetic diagram of an object. Key: (a) incoming information; (b) unprocessed information; (c) outgoing information; (d) information being processed; (e) resultant information; (f) original information; (g) processing of information; (h) intermediate information.

with the principles of construction of automatic measuring systems, [8], a block diagram of SIGMA-s was put together (Figure 2). The SIGMA-s breaks down into six blocks:

SIA-Ship measuring devices;
AIK-Autonomous measuring complex;
KIOSK-System for information exchange between ship complexes;
OSAK-Devices for exchanging information between ship and autonomous (automated) complexes;
SCC-Ship computer center;
CCC-Coastal computer center.

The algorithm for the operation of each automated complex is constructed in such a fashion that, without excluding the possibility of autonomous operation of the measuring devices, a possibility exists of combining all of the automated complexes into a single system.

Let us examine the algorithm of the operation of a measuring apparatus and the block diagrams which perform these algorithms. Figure 2 shows these block diagrams represented by 1 and 2. The /15

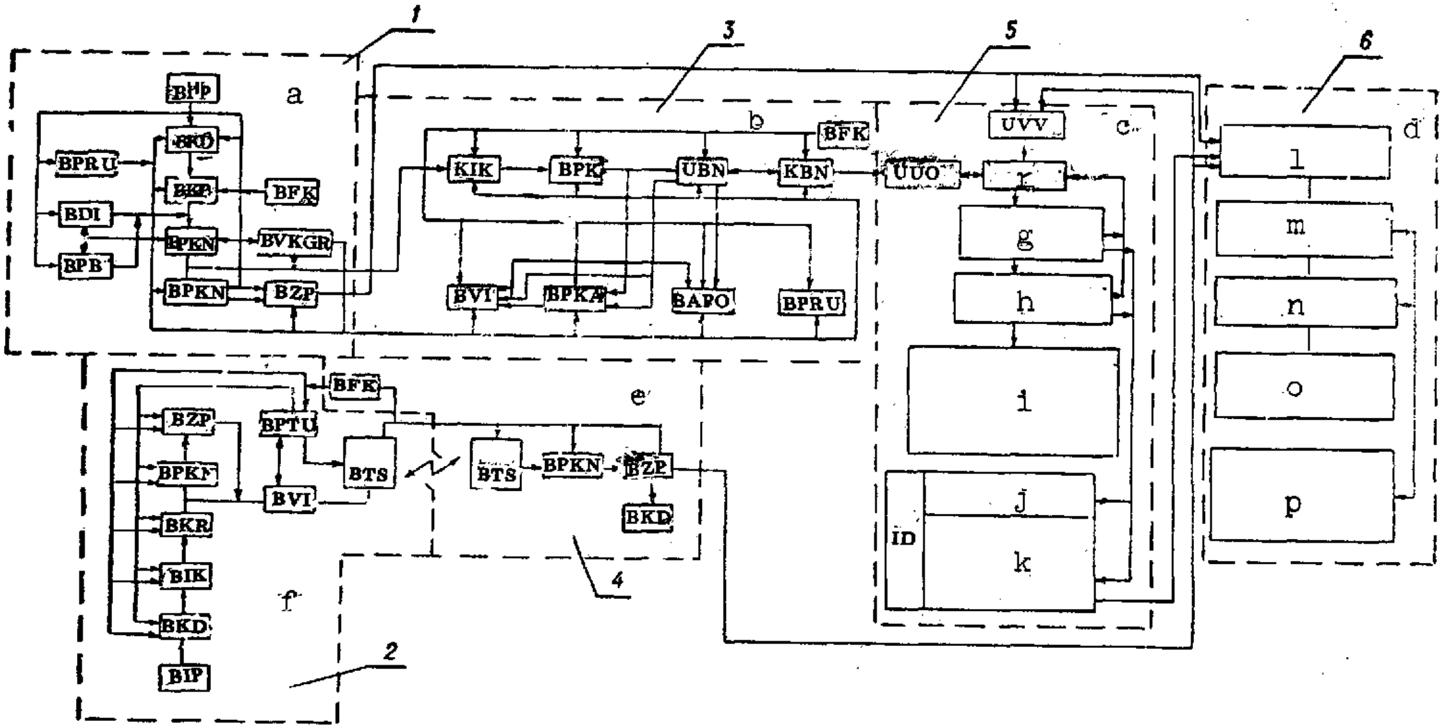


Figure 2--Structural diagram of SIGMA-s (a) SIA; (b) KIOSK; (c) SCC; (d) CCC; (e) AIK-2; (f) AIK-1: (g) preliminary processing of data; (h) complex processing of data; (i) decision on the correspondance of the results of the observation to the set goal; (j) output of operative data; (k) documentation of the results of the analysis (including on the technical media), (l) primary processing of data; (m) storage of intermediate information; (n) final analysis of information; (o) planning and control of expedition; (p) systematization, documentation and storage of information; (q) power supply for the computer; (r) computer memory.



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sequence of the measurement and the conversion of the results into the machine code is the same in both cases:

BIP-Block for measurement conversion. Transforms the physical parameter into electrical value.

BKD-Block for switching sensors. Feeds electrical signals from sensitive elements to analog-digital converters.

BIK-Block for measurement and coding. Performs analog-digital conversion of electrical signals.

BKR-Block for switching of registers of analog-digital converters. Connects output registers of the latter to the recording device.

BPKN-Block for transformation into the carrier code. Converts the information from the ATsP (Analog-digital converter) code to the recorder side.

BZP-Recording block. Records measured parameters.

BFK-Block for monitoring function. Checks operation of modules and blocks of automated apparatus.

In addition, the SIA must also include:

BPRU-Block for programmed and manual control.

BDI-Block for additional information which makes possible the input of service characteristics and parameters.

BRV-Block for manual input, allowing input of parameters whose measurement is still impossible to automate.

BVKGR-Block for visual control and graphic recording. Takes care of graphic form of recording of measurement data.

AIK includes the BPTU-the block for program control and remote control. It controls the operation of the AIK and changes the operating program on command from the SRV.

The measurement complex, which is constructed according to this block diagram, will be composed almost completely of unified modules and blocks, with a single system for output electrical signals from the primary measuring converters and will completely satisfy the requirements placed upon it.

The autonomous measuring system must have a coupling apparatus between the AIK and the ship computer. This coupling is accomplished by a complex for exchanging information between the ship and the autonomous complex of the AIK-2, whose block diagram is shown in Figure 2. The AIK-2 works according to the following algorithm:

(1) Receipt of information from the AIK-1 and the formation of appropriate code reports (performed by a block for information output, BZI);

(2) Transmission of information to the vessel and receipt of commands from the SRV (this is accomplished by a telecommunication device, BTS, located in the AIK-1);

(3) Receipt of information aboard the SRV and output of control signals to the AIK-2 (this is accomplished by a telecommunications device called BTS, mounted aboard the ship);

Recording of the information received on a technical carrier /16
in a form which is convenient for computer input (carried out by a device for recording information called BZP);

(5) Checking the received information to exclude false or erroneous material, the percentage of which may be very high when there is noise in the telecommunications channel (this is carried out by a block for monitoring the data, BKD);

(6) Data input into the computer (carried out by a device for data input, UVV; it is advantageous to use a table device for input into the computer).

A similar measurement complex solves the problem of automation of the collection and recording of hydrometeorological data on the technical carrier in a form which is convenient for input into the computer, and consequently, for the preparation of data for machine processing.

In order to automate the control of the experiment and the complex handling of the scientific information collected by marine expeditions (for example, for an operative evaluation of the results of a given experiment), it is necessary to collect and transmit the data to the computer in order to achieve centralization and to create a complex of devices for information exchange between the measuring complexes aboard the ships with computers and with one another, thus combining the ship's automated devices with the system.

The complex of devices for coupling must carry out the function of controlling the system and if the capacity of the computer is small, it must carry out the analysis (for example, statistical) and documentation of the data.

In its general form, the algorithm of the complex of information exchange of the ship complexes, made in the form of the block diagram shown in Figure 2, is as follows:

1. Connection of the measuring complexes to the device for buffer storage UBN (carried out by a switch on the measuring assemblies KIK and, if necessary, a block for code conversion BPK);

2. Buffer storage of the information (carried out by the UBN):

3. Recording of initial information on a permanent medium (carried out by the data output block);

4. Transmission of the stored information to the computer (carried out by the UBN and the switch on the buffer storage KBN which controls the UBN);

5. Retrieval of the analyzed information from the computer (carried out by the UBN and the KBN);

6. Registration of the analyzed information on a permanent medium, documentation of the data according to the established format carried out by the BVI and if necessary with participation of the converter block of the code-analog BPKA for plotting of graphs);

7. Performance of the analysis and several forms of handling of the data (carried out by the block for analysis and initial processing, BAPO);

8. Control of the operation and execution of the time synchronization of devices and blocks in the KIOSK and the ship measurement complexes (carried out by the block for programmed and manual control BPRU and the time block). /17

The machine time of the ship computer will be used mainly for calculation, since the input and output of the data is carried out through the buffer store of the KIOSK. The characteristic of the "Minsk-22" computer installed aboard the vessel is that, it cannot simultaneously solve problems and receive large amounts of information on a real-time scale. In addition, in the "Minsk-22" computer the volume of the MOZU (Internal Magnetic Storage) is small, and the high-speed operation is ten-fold less than in computers that have been developed recently. KIOSK compensates for the shortcomings of automated hydrometeorological systems, namely, the slow input of data from primary sources and the necessity for accumulating for processing large volumes of data that is diverse to a certain degree.

Connecting the measurement systems through a coupling apparatus with the ship's computer increases considerably the efficacy and completeness of data handling. The ship's computer, when feedback and BPRU are present in the KIOSK, can control experiments that are in progress and calculate model theories and hypotheses that are being checked. For this purpose the ship's computer must have some sort of archive and a system for information retrieval. Hence, we are justified in speaking of a ship's computer center organized on the base of the ship computer and supplemented by complexes of data handling between the ship complexes and a complex for information exchange between the ship and autonomous complexes.

Due to the problems that are faced by KIOSK as the center for switching messages possessing the necessary universality for collection and preliminary analysis of the data, it is desirable to use a small digital computer.

The block diagram of the "Minsk-22" corresponds to the block diagram of a computer and therefore has not been shown. Functions carried out by the SCC are shown in the general diagram (see Figure 2, position 3).

The presence of the SCC aboard scientific research vessels does not exclude the need for connecting the flow of information collected by the ships to the CCC (see Figure 2 position 6). The problems solved by the CCC are much wider in scope than the problems handled by the ship's computer center. Its development is planned on the base of the "Minsk-22" computer.

The principles for building ship automated systems for collection and analysis of hydrometeorological information aboard the SRV of the GUGMS, discussed in this article, can be carried out in the form of technical tasks for the construction of blocks in individual complexes of systems which are in a state of preparation.

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# SOFTWARE FOR THE SIGMA-s /19

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In view of the equipping of scientific research vessels of GUGMS with modern digital computers of the "Minsk-22" type, it has become possible to automate the process of initial processing of scientific information. An advanced project for a ship information hydrometeorological automated system called SIGMA-s showed the basic ways of solving the given problem [2]. For an effective introduction of SIGMA-s into practice of hydrological meteorological investigation it is necessary to have appropriate software for all hydrometeorological systems of the SRV.

The scientific information which is stored aboard the ship in the measurement complexes (IIK) may be divided into two forms: conditionally determined, obtained over rather long intervals of time and space (several hours and hundreds of kilometers, respectively), and random, obtained during time changes of less than an hour and extending within the limits of several hundred meters. The scientific information of the first kind is basic for the operational and scientific activity of forecasting and for scientific centers. This information lends itself to long term storage.

Random information is used for studying the nature and mechanism of small scale turbulent processes in the hydrosphere and atmosphere, as well as for evaluating the accuracy and discreteness of the observations. In our opinion, it is not advantageous and practically impossible to achieve long term storage of all random information which may be obtained by activating the technical complex of automatic information SIGMA-s [2]. In this case, the volume of the scientific data which is obtained from research vessels may increase practically without limit, since the time interval between the observations will measure fractions of a second. How much of this information must be less than the long term storage and how much must be destroyed after appropriate analysis, compression and accumulation of the original data will be known after a more prolonged utilization of any random information in practical and scientific applications.

We shall present rough estimates of the area required and the amount of machine time for the "Minsk-22" computer required for the storage and processing of data from a 100 day voyage of a single /20 research vessel of the "Professor Vize" type.

| Type of information | Volume of Information bits | | Area for punched cards, $m^2$ | |
|---|---|---|---|---|
| | Maximum | Average | Maximum | Average |
| Conditionally determined | $10^7$ | $10^6$ | 0.07 | 0.007 |
| Random | $10^{11}$ | $10^8$ | 700 | 0.7 |

It follows from the above data that no difficulties will be encountered in the storage and initial processing of the data with a volume of up to $4 \cdot 10^7$ bits. In the event that the volume of information increases due to random information up to $10^{11}$ bits, about 700 $m^2$ will be required for storage of this data on 80 punched cards with columns (p c), or 10 $m^2$ of storage space for microfilms (m f) and about $5.10^6$ hours of machine time for its analysis (in calculations on the "Minsk-22" computer). Note that these figures represent an estimate of the lower limit of the extent of these parameters: it is assumed that one punch card can take ten cubed bits, which is greater than the actual situation; 0.5 hour of machine time for analysis of $10^4$ bits is evidently not an excessive value. Storage of $10^6$ punch cards requires 7 square meters or 0.1 $m^2$ for microfilm [10]. These figures show that the volume of information from one voyage practically cannot exceed $10^8$ bits.

It follows from the above that in order to analyze random information on the SRV it is necessary to establish special analog devices (correlometers, etc.); it is not advantageous to store all of the random information for a long period of time, and it should be collected only for the solution of a specific scientific problem. Extreme, particularly interesting, data must be stored in the original form, most of it being accumulated by means of calculation of correlation instructional functions, spectral density, as well as the parameters of distribution and other methods of compacting information.

Hence, in the first stage of automation, in addition to developments of algorithms and technological systems for initial processing of scientific data on the SRV, it will be necessary to have the following:

a) To determine the optimum volumes and forms of information suitable for prolonged storage;

b) To determine what type of processing aside from initial processing of the original data should advantageously be conducted with the SRV digital computer and what kind should be carried out at the coastal computer center (CCC).

Let us examine the software system for the SIGMA-s. At the present time, there are some papers which have been devoted to the translation of analyses of individual forms of scientific information on a digital computer [16]. However, both the technological /21 systems and the algorithms for the solution of a specific problem do not exclude completely the role of manual labor in the process of primary processing of observation results.

By the primary processing of the results of the observations, we mean:

- Introduction of necessary corrections and coefficients;

- Interpolation for standard depth and altitudes;

- Isolation of special points and layers in the distribution of hydrometeorological elements along the vertical;

- Smoothing of the signals arriving from sensors in two and three dimensional space;

- Obtaining the corresponding derivational characteristics (geopotential with respect to temperature and pressure, etc.);

- Critical analysis of the results obtained (detection and correction of random and systematic errors);

- Obtaining established forms of representation (tables, graphs);

- Preparing the results of the observations for entry on a permanent medium DNI (compaction, coding);

- Recording of the scientific information on the DNI (punched cards, microfilms).

The complexity of these operations indicates that automation of the process of primary processing of the results of the observations cannot be viewed as a normal technical problem. The solution of such problems as the interpolation for standard altitude and depth, smoothing, determination of particular points and layers, as well as a critical analysis of the results of the observations requires the designing and carrying out of special studies.

Taking into account the complexity of the design and operation of the SIGMA-s [2], software for this system should be implemented in two stages.

At the present time, it is possible to put into practice for the purpose of hydrometeorological investigations programs for machine analysis of scientific data which free the observer from monotonous manual labor but do not solve completely the problem of automation. It is primarily the elements of primary analysis whose algorithms have been sufficiently well developed that are subjected to automation: Introduction of corrections, calculations, in some cases, interpolation and the basis of critical analysis, as well as the obtaining and printing of the established forms of representation of the results of observation. The technical diagram and the programs must be put together with an eye toward the possibility of their further improvement until complete automation both of the collecting process and the primary processing of the scientific data. At this stage, the process of primary processing of each hydrometeorological complex is algorithmized and automated separately for the purpose of scientific and methodical evaluation. The preparation of the original data for input into the computer is carried out both manually and automatically. Samples of punch cards must be made up according to a uniform design for /22
each hydrometeorological complex and the optimum quantity of primary data must be obtained to insure the necessary accuracy of further calculations on a digital computer.

At this stage, it is advantageous to carry out the particularly complicated operations of primary analysis of the data (selection of particular points and layers, in certain cases smoothing and critical analysis), by entrusting them to a specialist. At the same time, it is not advantageous to use the computer only for printing tables [15], since it can liberate the observer from various kinds of tedious calculations and consequently from the technical monitoring of the forms of representation. In addition, at the first stage of automation it is necessary to improve the existing methods of primary analysis and the form of representation of the results of the observation. In this connection, as the programs for automated analysis of individual hydrometeorological complexes are worked out and introduced, it will be necessary to change accordingly the operating instructions and directions.

The algorithms for the primary analysis of hydrometeorological complexes have common features, so we shall examine one software flowchart for the first stage of automation of the primary analysis of the results of observations aboard an SRV (Figure 1). From the analysis of this block diagram it follows that the system for automated primary analysis consists of individual blocks (subprograms).

The subprograms for input and technical monitoring are made up primarily of codes and models of punching, according to which the scientific data is entered on the technical carrier. By technical monitoring, we mean the checking of the input and punching of the data, carried out by the method of comparison of sums, alogisms, and other methods which are familiar from the practice of operational functioning of forecasting centers [1, 17].

The sorting block performs the distribution of information which comes into the digital computer during the observation period by complexes into the memory of the machine and also forms the body of operative information. Data used in various hydrometeorological complexes are stored in the latter from time to time, for example, meteorological data, speed and direction of the vessel, coordinates, etc. In this case, there is no need for inputting these parameters for each complex separately. When necessary, the corresponding distinctive features will be formulated and added.

The digital computer stores the value for the various corrections and conversion factors in the form of tables or analytical expressions. Along with a block for inputting corrections and coefficients, various kinds of instrumental and navigational corrections in the observation results are implemented.

In conjunction with the automatic inputting of signals from various hydrometeorological sensors into the digital computer, it is unavoidable that there will be various kinds of random errors--
scatter. In order to exclude them, smoothing of the primary results /23
is carried out primarily by the method of polynomial approximation or a sliding average. It is necessary to exclude disturbances less than the minimal characteristic size, for example, a sharp change in the wind direction at high altitude, in a layer several dozens of meters thick, etc.

<u>Isolation of particular points and layers</u>. In the course of /24
hydrometeorological observations at sea, data on the layer of the "discontinuity" are particularly interesting, and in the troposphere we are particularly interested in the tropopause and various particular points in the vertical distribution of meteorological parameters. Obtaining these data is one of the most complicated problems in the process of primary processing of scientific data. Therefore, in developing programs for automated

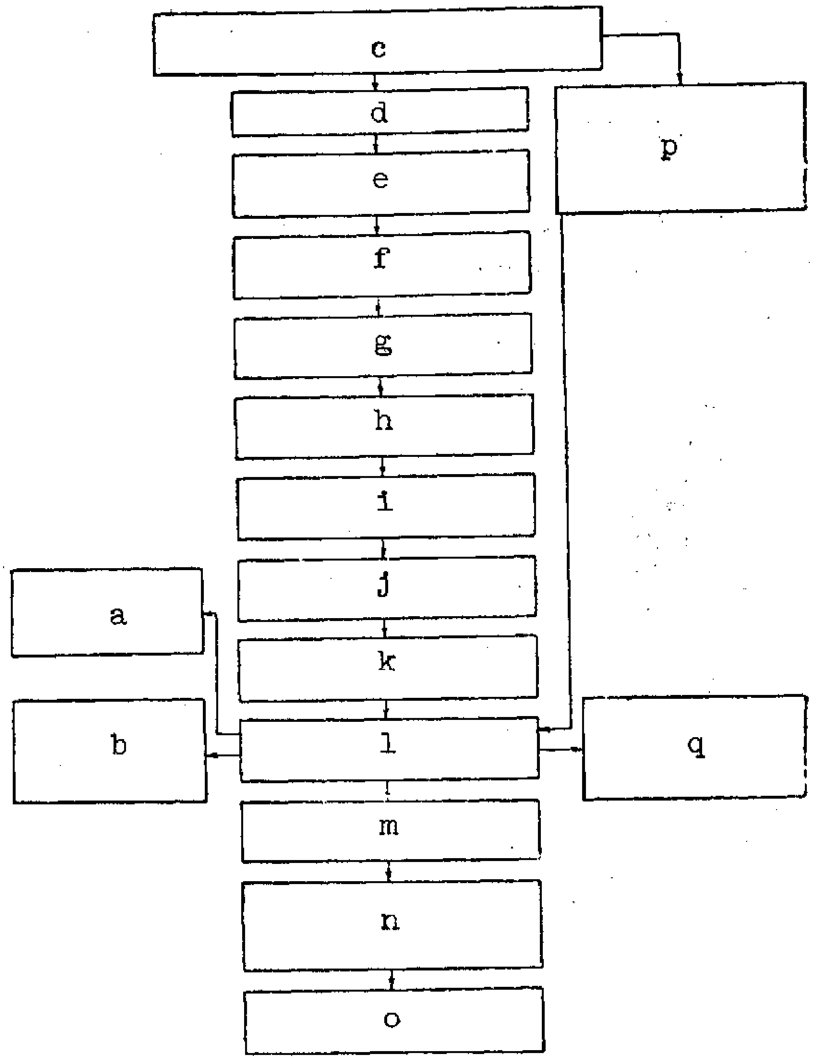


Figure 1. Block diagram of the system for primary processing of scientific information. Key: a-input to CRT (cathode ray tube); b - output to teletype; c - data-measuring complex (IIK); d - input; e - technical monitoring; f - sorting; g - introduction of corrections and coefficients; h - smoothing of signals of sensors; i - interpolation for standard level; j - isolation of particular points and layers; k - obtaining arbitrary parameters; l - critical analysis; m - obtaining and printing the form of representations; n - preparation for entry in the DNI (compaction, coding); o - entry on the DNI; p - calculation of statistical parameters on analog devices; q - recording on the NML (magnetic tape storage).

processing of aerological and deep-water data, it is necessary to pay particular attention to this block.

Obtaining arbitrary characteristics. In calculating the number of parameters on the basis of information on other parameters, for example, distance, speed and wind direction, temperature and altitude of pressure, etc., calculations are carried out basically according to generally known algorithms.

The problem of critical analysis in automation of primary processing has thus far remained practically unsolved. The most widespread methods involved in the function of forecasting centers are static monitoring of aerological data at a single point [4], and horizontal monitoring of the data from other stations using optimum interpolation [5]. The latter monitoring method provides particularly good results with a dense network of stations. It is possible to detect both random and systematic errors in measuring. However, both of these methods of monitoring use a rejection criterion based on the difference between the analyzed elements and the results of a check of the equation of statics and of the optimum interpolation, and these do not have a sufficiently reliable probability base. The probability base is possessed by statistical methods that are based on information concerning the law of distribution and the natural variability of a given hydrometeorological parameter. This method has been described in [3] as it applies to small unrelated samples, and for related samples in [6, 7].

Statistical monitoring is employed in the organization of a technological system of automated processing of aerological data [13, 14, 18]. However, in this case the mean square deviation which characterizes the variability of the parameter being analyzed is calculated with a consideration of the extremal terms of the sample which, in the first place, may be viewed as doubtful. It may be suggested that the results of a check of the efficiency of machine monitoring may be higher if the monitoring algorithm is structured somewhat differently. In calculating the parameters of variability on the basis of the data of the sample being analyzed, the extremal values of this series must be excluded. In this case, monitoring the data amounts to checking the extremal values. If they lie within the reliability limits that are found, the analysis is stopped, the material being considered reliable. If the extremal values turn out to be outside the limits of reliability, the following extremal elements are excluded from the theories under analysis and the entire procedure is repeated until the extremal values fall within the limits of reliability. Results of observations which do not /25 fall within the limit of reliability are considered questionable and are subjected to further analysis.

The algorithm of the statistical expression of coarse, random errors may be constructed as follows: The parameters that are necessary for calculating limits of reliability are obtained as the result of a statistical processing of many years worth of hydrometeorological elements. This makes it possible to reduce to a minimum the expenditure of machine time to check the information and determine the random and systematic errors (if the average values are checked) which go beyond natural variation of the elements in question.

It must be pointed out that in areas with a dense network of stations the most efficient method of checking is that of horizontal matching of synchronic values for the field of the hydrometeorological element being analyzed; this makes it possible to find the smallest errors in the data of both a random and systematic nature in comparison with other methods of checking. However, in order to adopt an objective criterion for analysis it is necessary to perform considerable statistical investigation for the purpose of obtaining estimates of the law of distribution, the norm, and the mean square deviation of the errors in the method adopted for interpolation for locally uniform regions according to the parameter being analyzed.

The algorithm for checking the hydrometeorological data aboard scientific research vessels essentially requires construction on the basis of agreement of the results of observations from all hydrometeorological complexes. Statistical monitoring can also be employed, but the criteria for correction must be obtained for regions with locally uniform variability for each hydrometeorological element and season. In addition, in the information reference bank (SIF) of the SRV it is advantageous to store the results of observations conducted at the same time aboard vessels located nearby.

For the purpose of checking it is desirable to use operational plotting of curves of distribution of hydrometeorological elements (for example, air and water temperatures measured vertically) on a cathode ray tube or other device with sufficient resolution. This will allow the experimental specialist to evaluate the quality of the data he has obtained in comparison with many years worth of data of the elements being analyzed in the given region and for a given time of year, as well as with the results of previous observation periods aboard the SRV. The screen of the tube displays calibration curves for distribution and their reliability limits for a given level of significance.

Unquestionably, the operating conditions of scientific research vessels must be such that they employ methods of checking that are based on determination of the agreement of the results of observations with the equation of statics.

Thus, in order to develop a system of automatic monitoring of the results of observations aboard the vessels of the GUGMS, it was necessary to conduct a statistical analysis of the data in the operational regions for the purpose of determining locally uniform regions, with respect to variability of the elements to be analyzed and to develop algorithms of the alogisms for all forms of observation. The operational information was sent out on the teletype in the Baudot code in the form of an appropriate telegram and is then broadcast. /26

At the first stage of automation, the standard table and graphs are printed. In the course of this stage, optimum forms of representation of the scientific data are worked out which are put into practice in the second stage. This involves solution of the problem of the advisability of transmitting various booklets and tables under the conditions when all of the information is stored on long-term data carriers. At the present time, due to the fact that we still do not have sufficient reliable long-term data carriers, the storage of material in the form of tables and graphs is a reliable form of providing a backup that allows reconstruction of information on any technical carrier. Magnetic tape stores all the information from the voyage as it progresses in a form which is convenient for use on that voyage.

In the block in which data is prepared for recording on a permanent medium, there is a filtration of information for the purpose of excluding excess material and compaction for the purpose of accumulation of data. Calculated parameters are excluded (geopotential, dynamic depths, etc.), and the optimum stages of discreteness are chosen both for time and for space, making it possible to develop the distribution of hydrometeorological elements with respect to both time and space. Therefore the curves and the fields of distribution of these elements are broken down into their individual components or approximated by other methods. The coefficients of expansion are entered in the DNI. In the first stage of automation, the optimum algorithm for filtration and compaction are worked out, and also the coding of the information prior to its entry in the DNI.

To develop both the ship and coast information reference bank, the data is entered on permanent media. Punch cards and microfilms are used as the DNI [9, 10]. In the case where ships have no output puncher for punched cards or facilities for microfilming the data in the appropriate form, the information is sent out on a telegraph tape which is transferred to the DNI at the coastal computer center through the computer.

The development of a library of standard subprograms which carry out these stages of primary processing makes it possible to automate completely the handling of data from all of the hydrometeorological complexes of the SRV.

In addition to the primary processing of the observation results on the computer, it is also considered possible to perform a scientific analysis of the data. However, a special problem with the computer is the primary processing of the scientific data for the purpose of representing it in a form convenient for further utilization for scientific purposes and also solving operational problems having to do with navigation and controlling the ship. In this connection, the first stage of operation deals not only with the development of algorithms and programs for primary processing of data from individual hydrometeorological complexes, but also solves the problem of differentiation of the flow of information and takes into account the optimum discreteness of the measurements, the volume and form of calculations on the SRV computer and in the coastal coordinating computing center (BKVTs). /27

It must be pointed out that when developing an automated complex of measurements it is not advantageous to develop various complex logical and arithmetic devices, for example, blocks for decoding operative synoptic telegrams and calculating the true wind. They lead to considerable complication and consequently raises the cost of the ship's automatic meteorological station. The computer aboard a scientific research vessel can solve any logical and arithmetic problem more accurately and faster than any non-mass-produced device. Therefore, the development of technical complexes must be carried out in close correlation with the development of software for these complexes. In this case, one can see what sort of logical and arithmetical operations (making of corrections, etc.) it is advantageous to solve in developing measuring devices and what kind can be handled through programming on a computer. In this case, the technical complex is less costly and reliable in operation but the cost of the additional machine time is negigibly small.

On the second stage of automation, a uniform ship information-control automated system for primary processing of scientific data is developed aboard scientific research vessels [2, 8, 11, 12], generalization and unification of algorithms and programs of individual hydrometeorological complexes takes place, in addition to the development of control programs and the development of operative information-reference banks. These banks are intended for

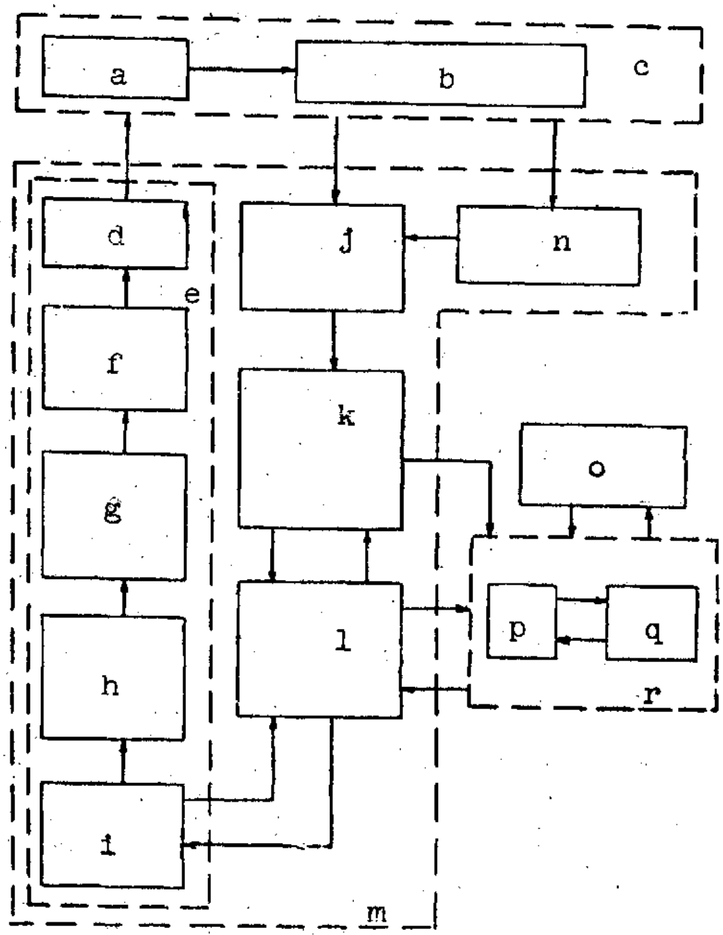


Figure 2--Block diagram of the organization of the automated data system (AIS). (a) sensors; (b) translation into digital code and punching; (c) IIK; (d) control of the experiment; (e) command control; (f) determination of control algorithms; (g) determination of the criterion of optimality; (h) mathematical description of the process being investigated; (i) statement of the problem of controlling the object; (j) primary processing of the data; (k) automatic retrieval and output of data by means of the IPS; (l) operative scientific processing of data and its use; (m) SIUVK; (n) calculation of the statistical parameters on analog devices; (o) scientific research work at the institute; (p) VTs; (q) SIF; (r) BKVTs.

the storage, automatic retrieval and output of data on command from the investigator by means of a data retrieval system (Figure 2).

Hence, it is suggested that an automated system be developed which interconnects with all hydrometeorological complexes (SIUVK). By means of such a system, an express information service can be set up and measures adopted to correct the experiment. The exchange of the preliminary results of analysis of the data of observations between the ship and the coast coordination computer center makes it possible to correct the experiment as it is going on. The BKVTs will concentrate the archives of the observation and it is here that the leading scientific specialists will work.

Consequently, after the development and introduction of hydrometeorological research the SIGMA-s will be able to begin its work to develop algorithms for the control of the experiment. /28

The process of automation of the control of the experiment must also be carried out in two stages. In the first stage, the presence of a specialist is necessary in the control process. Control is carried out according to the following algorithm: All of the hydrometeorological complexes begin automatic recording with a given degree of discreteness, data enter the analog devices (AM) which compute their correlation functions and spectral densities, and also the space and time gradients, then an analog or digital analyzes the results of the calculations of the AM. As a result of this analysis, using the given criteria, recommendations are made for optimum discreteness of recording. The optimum degree of /29 discreteness, obviously, must ensure smoothing of the turbulent vortices of the scales which are smaller than characteristic ones which are obtained on the basis of a preliminary study of the statistical structure of the processes and field being studied. At this stage the specialist analyzes the validity of the recommendations obtained and changes the degree of discreteness of the recording if there is no feedback between the computer and the measuring complex (IK).

At the second stage of automation of the process of the control of the experiment, which is carried out following total introduction of SIGMA-s and its corresponding improvement, the computer has a feedback connection to the measuring complex. The extent of study of physical processes taking place in the atmosphere and hydrosphere must be sufficient for setting the reliable criteria in terms of variability and spectral characteristics in choosing the optimum degree of discreteness of the recording. In this case there is an automatic recording, analysis, and control of the measuring apparatus according to a given algorithm. It is advantageous in this regard to use the IK⟷AM computer system (see Figure 2). In this case, there is no need for the digital computer to work on a real-time basis. Analog devices will work on a real-time basis.

The algorithm for monitoring the experiment can be described in a more concrete fashion after carrying out a sufficient number of experiments. In order to solve the problem of optimum punching of random information it is necessary to set up the equation of the experiment starting with the time of introduction of the high speed apparatus for recording the results of measurement. Therefore, in working out the technical problem for construction of analog devices it is necessary to provide for the possiblity of direct input of the analog from the sensors, calculation of the correlation and structural function and spectral density. In addition, it is necessary to allow for the possibility of automatic input of a puncher in increasing the given level of the gradient (structural function according to shift 1), excluding it when this value is lowered. In this case, we will obtain new information regarding the process under study with minimum expenditure of time on the part of both the specialist and the digital computer.

On the basis of the above we can draw the following conclusions. At the first stage of automation there is a development of a model of the software for individual hydrometeorological complexes of the SIGMA-s and a refinement of the principles of the design of the information-reference banks and the design of an automated information-control system.

In the course of carrying out the second stage, there is a unification of algorithms and programs of the primary and scientific analysis of the hydrometeorological data from individual complexes and a single ship's information-control automated system for primary analysis of scientific information aboard the SRV is created.

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N75 13441

# THE PROBLEM OF ORGANIZATION OF A COASTAL COORDINATING COMPUTER CENTER /31

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I. I. Lodkin

The development and putting into practice of hydrometeorological studies by ship automated information systems [2, 5] requires the development of an automated data system which combines and coordinates the work of individual subsystems on the basis of a coastal digital computer.

The existence of a closed automated system for collection, primary processing, analysis, storage and propagation of the necessary information makes it possible to carry out the optimum planning and control of an experiment, which increases the efficiency of experimental investigation of the physical state of the atmosphere and ocean.

At the present time, within the system of the hydrometeorological service of the USSR, work is going forward on an intensive basis to develop a single center for the collection, storage and propagation of organized hydrometeorological data on the basis of modern computers [7].

The regional scientific research centers which are carrying out studies of hydrometeorological processes and fields extending over enormous areas of the earth must also have their own information subsystems that feed into the common system for the collection, storage and dissemination of information [8].

As a result of scientific studies carried out in the Arctic and Antarctic by the scientific research institute and the hydrometeorological center of the USSR, it has been found necessary to develop regional and territorial data centers (TGMTs) on the basis of which it has been proposed that an automated data system for collection, primary processing, storage and propagation of results and observations from the network of stations be organized [1, 11]. According to this system, the primary processing of the measured parameters, formation of operational telegrams and their transmission to the forecasting centers will be carried out at the TGMTs. In this case, it will be possible to ensure the necessary operational basis for inputting data to the corresponding superior subdivisions, and then compressing the information prior to its translation along communications channels over long distances. However, at /32 the present time a proposal has been made to change the system: the results of the observations from all the stations will be stored and processed at four regional hydrometeorological centers (RGMTs). A change in the system of construction of the general automated system, transmission by the AANII scientific research vessels, as well as the construction of the Antarctic computer center at the Molodezh station has expanded the problems and changed the structure of the automated data system (AIS) of the Arctic and Antarctic Scientific Research Institute (AANII).

In conjunction with the development of a single data center for the hydrometeorological service of the USSR, there may be some discussion of the advisability of organizing automated systems for storage and retrieval in individual scientific research institutes. However, it is difficult to imagine the possibility of effective utilization of modern computers which are located at the scientific organizations and the performance of serious studies without some kind of specific volume of scientific data recorded on permanent media (DNI), stored in the information-reference banks (SIF) of the particular institute. The data in the SIF of the Scientific Research Institute must consist of duplicates of the DNI which come in from the appropriate regional centers and the Obninsk branch of the GMTS. In turn, the large scientific research departments send to the data collecting centers duplicates of the scientific data on the DNI, obtained as the result of performance of physical experiments.

Hence, in the large scientific research departments, the GUGMS of the USSR must develop their own automated information systemsin accordance with the tasks placed before them [8].

The purpose of this paper is to describe the automated information system for the collection, primary processing, generalization, storage, retrieval and propagation of scientific information that reaches the AANII. For scientific studies, data are used here which come from various observation points (Figure 1). The annual influx of information along the network of stations of the Arctic and Antarctic Institute (drifting and Antarctic stations, SRV) consists of about $2.10^7$ bits (Table 1). This includes only the necessary observations. The development and putting into practice of matters of collection with automatic recording of information on a technical carrier in a form suitable for immediate input into a computer will increase the flow of data by several orders of magnitude [2, 5]. In the near future, the data banks of the Institute will be filled with information that will have a volume of at least $2\text{-}3 \cdot 10^9$ bits (2-3 million punched cards per year). Moreover, in order to study the macrocirculatory atmospheric processes, the results of observations from the files of the Obninsk division of the GMTs will be added.

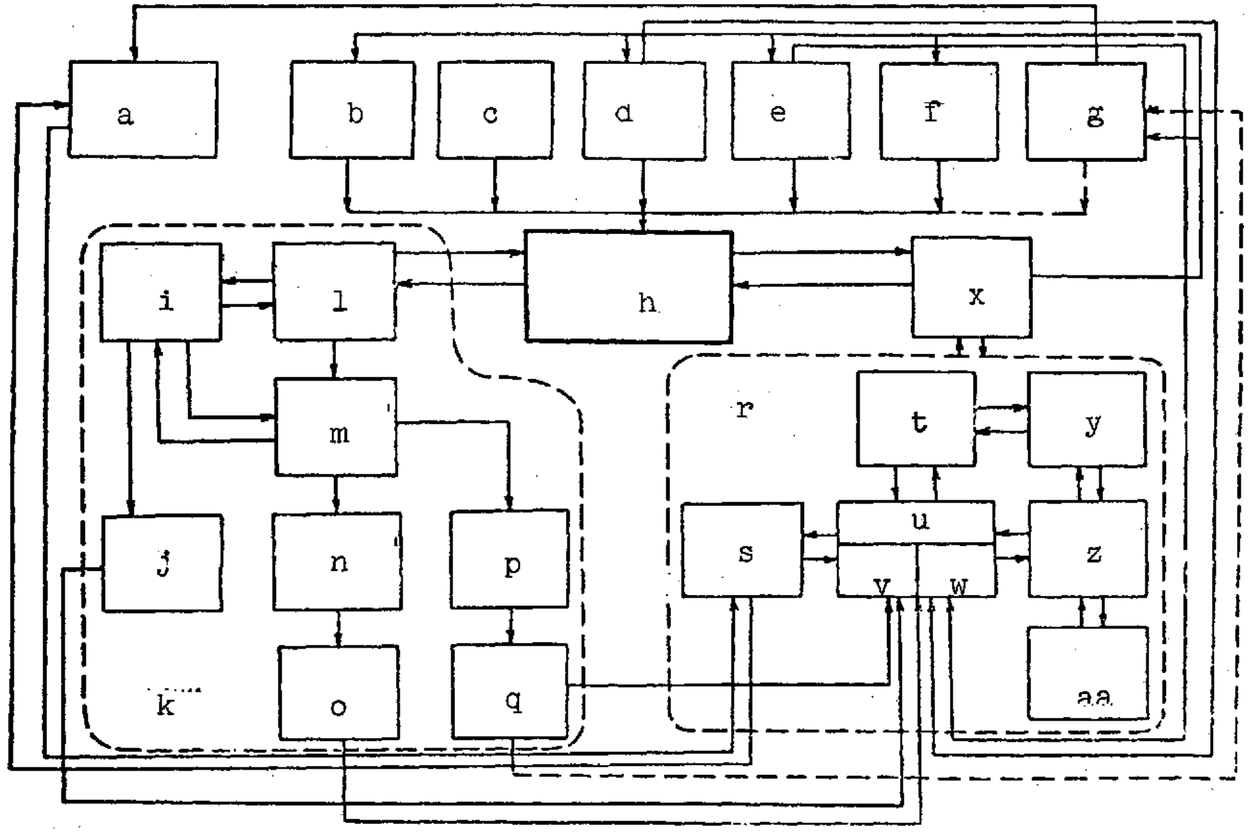


Figure 1.--Block diagram of the flow of information to the BKVTs. a - GMT and RGMTs; b - SP (Monitoring Station); c - DARMS (Drifting Automatic Radiometeorological Station); d - SAE (Soviet Antarctic Expedition); e - SRV; f - ship without computer; g - polar stations; h - computer; i - output to CRT; j - photography; k - AKOI (Automated System for Data Processing); l - technical and critical control; m - primary processing; n - sorting and condensation; o - recording on DNI; p - output on ATsPU (Alphanumeric Printer); q - printout; r - SIF; s - duplicate; t - IPS; u - archive; v - document; w - DNI (Digital computer); x - NIR (Scientific Research Work); y - SAM (Punched card machine); z - production; aa - coding microfilm.

Volume of Information (in Bits) Reaching the AANII Each Year (From All Stations and Ship Voyages)

| Type of Information | Polar Station | SAE | SRV | SP | Total |
|---|---|---|---|---|---|
| Meteorology | 119,800,000 | 7,400,000 | 1,300,000 | 3,000,000 | 131,500,000 |
| Actinometry | 12,300,000 | 5,300,000 | 700,000 | 2,100,000 | 20,400,000 |
| Aerology | 35,000,000 | 2,000,000 | 1,200,000 | 1,500,000 | 39,700,000 |
| Oceanology | 160,500,000 | -- | 2,000,000 | 100,000 | 162,600,000 |
| Total | 327,600,000 | 14,700,000 | 5,200,000 | 6,700,000 | 357,200,000 |

The observation points from which the data come into the memory banks of the institute may be divided into those which are equipped with computers and those which are not. At the present time, computers can be found at the AANII, aboard the SRV "Professor Vize" and the "Professor Zubov", as well as at the Molodezhnaya station in Antarctica.

Aboard the "Professor Vize" and "Professor Zubov," there are ship information hydrometeorological automated systems (SIGMA-s) [2], which make it possible to perform the basic stages of primary processing of scientific data, with the exception of storage of the information on a permanent medium [5]. The data which are subjected to long-term storage are recorded on the ship computers on an intermediate data carrier (punched paper telegraph tape), which is sent to the coastal computer where it is recorded on the DNI.

On the basis of the "Minsk-32" computer in Antarctica, at the Molodezhnaya station, an Antarctic meteorological center (AMTs) has been organized, whose basic functions will be the collection of operational hydrometeorological data along radio communication channels, sorting, development and transmission of lists of addresses preliminary processing, prognostic activity, generalization and scientific analysis of the results of observations at the Soviet and foreign Antarctic station.

The development of an automated meteorological center equipped with a computer in the Antarctic, with corresponding software, will make it possible to reduce considerably the time between the collection and utilization of data, and will also improve the quality of the circulated report. Prior to the development of this center, the results of the observations of the

Antarctic stations had to be processed aboard the ship computers during the return of the next Soviet Antarctic expedition.

The results of observations on the drifting automatic and non-automatic stations, as well as on ships not equipped with computers, are transferred to the technical carrier in a form which is convenient for direct input into the computer, and reach the Institute, where all of the stages of primary processing are carried out [5]. Duplicates of the DNI of the materials from the expeditions are sent to the data collecting center. /35

The data from observations of polar stations are sent to the appropriate regional centers, where they are subjected to primary processing. At the AANII, the results of the observations of the expeditions of the Institute are stored on DNI, as well as the necessary duplicates (required for solution of specific scientific problems) of data on the DNI from a specific network of stations, transmitted from the corresponding data collection centers. The latter part of the information will be constantly renewed (about $6.10^8$ bits).

In order to carry out the processing and storage of such a volume of data (approximately $2\text{-}3.10^9$ bits per year), as well as for coordination of the work of the ship and Antarctic automated subsystems, it is necessary to organize the coastal coordination-computer center (BKVTs), on the basis of which the automated system for collection, primary processing and analysis, storage, retrieval and propagation of data from expeditions will be designed.

Let us trace the path of the scientific data that reaches the BKVTs (see Figure 1). At the present time, all of the information from expeditions, before it goes into the archives of the BKVTs, passes through the computer. The results of the observations aboard the research vessels in the automated system for data processing (AKOI) are transferred to DNI, and the tabular materials, when necessary, are printed and transferred to the archives. For these purposes, the AKOI must be equipped with a microfilm facility and duplicating equipment.

The data in the archives for the computer will be stored in binary codes on punched cards or microfilm, which may break down due to the fact that it has to be fed into the computer many times. In this connection, prior to the development of a reliable permanent medium for information, the process of primary processing in the AKOI must be terminated by the accumulation and plotting of appropriate graphs and tables, as well as their duplication in necessary amounts, which will make it possible to develop the reliable duplicate copies of the information.

Consequently, in the information-reference bank (SIF), depending on the form of the carrier, the information will be sent into the document archives or the computer. The information reference bank must be equipped with appropriate devices for producing the DNI (punched card tabulators), SAM, apparatus for copying microfilms and documents. In addition, the SIF must have appropriate mathematical support organized at the data retrieval system which is based on the computer and the SAM.

Hence, in the first stage of automation, it is necessary for the coastal coordination-computer center to organize an automated complex for the processing of data and an information-reference bank which will allow input into the computer, primary processing and analysis, transfer to DNI, duplication of tabular and graphic materials, storage and retrieval of data and their production.

The execution of these measures considerably increases the efficiency of scientific research at the institute and makes it possible to achieve a solution of one of the basic problems of the BKVTs - the planning and the development of concrete recommendations having to do with the conduct of complex expeditionary research. This problem will be solved on the basis of an operative exchange of preliminary results of the analysis of data from a physical experiment between the scientific research vessels, the Antarctic meteorological center and the coastal-coordinating computing center, as well as on the basis of an objective analysis of the hydrometeorological fields and processes on the basis of the data of previous observations [8]. Hence, the organization of the BKVTs will speed up the development of recommendations concerning the density and time frame for conducting measurements on expeditions and at stationary points as a function of the problems with which they must deal. /36

The development of such a closed system can be carried out in the course of the second stage of automation.

The author of [5] discusses in detail the functions and structure of an automated system for data processing for the SRV, which essentially is the same for the BKVTs with the exception of recording on DNI and duplication of tabular materials.

Organization of the information reference bank.

The information that reaches the SIF is divided into two varieties:

1. Binary, recorded on a technical carrier in a form which is convenient for inputting into a computer;

2. Documentary, in the form of tables, charts, graphs, and so on.

At the present time, there are about 4,000,000 punched cards and 10,000 units of documentary information at the Arctic and Antarctic Scientific Research Institute. As the flow of information increases, ten years from now the files will take in another 15,000,000 punched cards and 160,000 units of information (by units of information, we mean calculation units: files, atlases, and so on). Therefore, it will be necessary in the future to go over to microfilming of the binarized and documentary data. Microfilming is a tedious and costly method of duplicating informational materials. It makes it possible to reduce the area occupied by the files and also to avoid damage to original documentary materials. Microfilming is a means of systematization for several forms of informational retrieval [9].

In organizing the microfilming it is necessary to observe strictly the conditions for storage of microfilms [3]. /37

Information Retrieval

Solving this problem is the responsibility of the information retrieval system (IPS), which makes it possible to conduct a multiaspect search in the SIF [10].

Any IPS consists of an organized combination of the following methods and means:

a) A formalized (machine) language;

b) Algorithms for translations from natural language of information materials to the specific formalized language and vice-versa;

c) Retrieval algorithms;

d) Technical devices, computer, SAM, selectors, etc.;

d) Devices for inputting and retrieving information.

There are two types of IPS: documentary and factographic. In the documentary IPS, an inquiry will yield only the address of the documents, while in the factographic one obtains the answer immediately to the question in which one is interested.

Figure 2 shows a block diagram of the organization of the IPS. /38
Blocks 1 and 2 serve for the input of information into the passive store and for preparation of the translation of information and

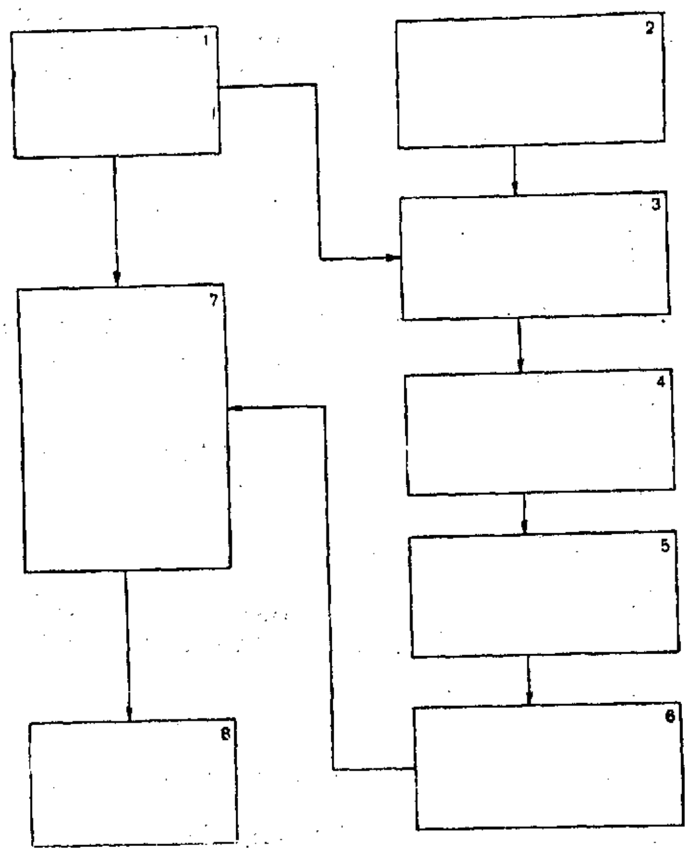


Figure 2--Block diagram of the organization of the information retrieval system (IPS). 1 - input of information (data load); 2 - input of information questions; 3 - translation of information to information-reference language; 4 - body of retrieval samples of documents (active storage IPS); 5 - comparison of data inquiry with inquiry sample of document; 6 - output of addresses of documents; 7 - storage of information (path of storage); 8 - output of information, in response to an inquiry.

inquiries into information-retrieval language (IPYa). The content of any document which reaches the input of the IPS may be described by a group of symbols (descriptors) which disclose the contents of a specific document. In block 3 is a translation of the incoming information to IPYa, i.e., each document (previously given a certain number) is coded with a number of descriptors. The number of descriptors that are used for coding a specific document constitutes the retrieval pattern of the document.

The body of retrieval samples makes up what could be called the "active" store of the IPS. The active and passive stores will be combined in the factographic IPS. There are two methods of organization of the body of retrieval samples of documents: (a) filing by document, (b) filing by semantic criteria (c) inverted method [4] and these two systems are shown in figures 3 and 4. /39

In the filing of the body of retrieval samples by document, each unit of information is a recording of the retrieval sample of one document with an indication of its serial number (address) in the "passive" store [9].

Retrieval is carried out by calling for the retrieval samples in order together with their serial numbers (addresses) into the block of the comparison device 5, in which a gradual comparison of descriptors of the inquiry with the descriptors making up the retrieval sample of the serial document is composed. If all the descriptors of the inquiry are found in the retrieval sample in question, in block 6 the consumer of the information will receive a number (address) for the document.

When the retrieval samples are filed by semantic criteria, each unit of information in the "active" store will have only one descriptor, together with the numbers of all the documents in whose retrieval samples the descriptor in question can be found. When searching by the inverted method for the location of the retrieval samples, it is necessary to eliminate all the descriptors that go to make up the informational inquiry and then by gradual comparison find the numbers of those documents which figure in all the descriptors that are included in the inquiry.

In the photographic system in block 8, the material of interest appears directly, for example, alphanumeric printout, skipping block 6.

Depending on the volume of the bank, the method of storage, the rate of output of information and so on, the IPS is developed on the basis of various technical criteria.

Document

descriptor

descriptor

⋮

descriptor

Document

descriptor

descriptor

⋮

descriptor

Document

descriptor

descriptor

⋮

descriptor

Figure 3--Arrangement of documents in the "active" store of the IPS

Descriptor

document

document

⋮

document

Descriptor

document

document

⋮

document

Descriptor

document

document

⋮

document

Figure 4--Location of information in the "active" store of the IPS on the basis of semantic criteria.

## Storage and Retrieval of Microcopies on Aperture Punched Cards

Punched cards with microfilm mounted in them are called aperture punched cards. They are punched cards with holes punched around the edge or else they are the standard 80 column punched cards. These cards, equipped with appropriate microfilms, can be sorted and retrieved in any fashion [6].

When large amounts of information are stored, it does not always make sense to use the aperture cards for retrieval because of their high cost and rapid wear. Another type of aperture card is the "classeur" card. Here the film is mounted in special "classeurs"--covers made of transparent paper or acetate material. The technique /40 of edge punching can be used on such covers [6]. The K5 punched card is used for them, with two rows of holes along the edge. On one side of the card there are vertical covers measuring 35 x 105 mm made of transparent polyethylene film in which the photomicrographs are kept. When in use, they are pulled out and inserted in the apparatus to read the microfilm.

## Information Retrieval Using the 80-Column Punched Cards for Machine Sorting

In order to retrieve information on the basis of various characteristics, each document is assigned an 80 column punched card.

By means of a descriptor dictionary, each document is encoded by the method of coordinate indexing, i.e., the semantic values are expressed by appropriate key words. The digital value of the code is transferred to the card by punching the appropriate holes in it. Retrieval of the document on request is performed as follows: the sorting machine goes through all the punched cards in the volume of encoded information comparing the codes of the desired samples of documents recorded on these punched cards with the code of the retrieval request. When the established coincidence criteria are satisfied, the sorting machine picks out the specific punched card from the main body of material and directs it into a special receiving pocket. This punched card should show the address number of the desired document.

The advantages of this method of processing microfilm to information are obvious. The bank of material is protected against rapid wear, since it is not necessary to search directly in the store (as is the case when using punched cards with aperture); the information retrieval system does away with the need for a card file, since there is no need to use an alphabetical card file of descriptors with the numbers of the documents inscribed on them for each descriptor, and the retrieval can be done according to various aspects.

Obviously, with this type of organization of the bank it is necessary to have considerable preparatory work to put together the descriptor dictionary and to encode each document. However, this is very promising for more efficient utilization of microfilm information.

Factographic System for Information Retrieval with Roll Storage of Microfilms on Selectors

At the present time, in order to retrieve microcopies of documents on the basis of their address numbers at the VINITI*, a selector called the "Poisk-OK" has been designed which combines a device for storing microfilms, automatically finding the desired information and a photocopying device that makes it possible to obtain electrographic copies of a document in its natural size. /41

As the information carrier in the selector, spools of microfilm are used. The capacity of a spool is 250-270 meters (5,000 frames) on 35 mm unperforated positive film. The rate of travel of the microfilm is 0.67 meters a second.

Retrieval of the desired information is accomplished by comparing the address code with the inquiry code. When they coincide, the frame with the microcopy of the document is projected on a transparent screen on which the image of the document will have the dimensions of the original. The average time required to find a microcopy of a document on the spool containing 5,000 frames is no more than 4 minutes.

Using any IPS requires considerable work to put together the descriptor dictionary and the code. All of the documents are subjected to analysis, then the choice of terms is made which discloses the essence of the document. The next step is to record the results of the analysis on the information carrier. It is only then that the search can be made.

Factographic System for Information Retrieval Using a Computer

The AANII presently has about 4,000,000 punched cards in machine code. For efficient use of the information which is on these punched cards a number of programs have been developed for retrieving average monthly hydrometeorological data. The programs

*All-Union Institute of Scientific and Technical Information are designed for retrieving information on combinations of any characteristics that go to make up a specific model of perforations for any complex.

Essentially, the body of information can be arranged in any sequence. It is not necessary to separate one model from another or one complex from another.

The algorithm for automated search in the factographic system has the same form as for retrieval of information in a documentary IPS. However, at the output of the system we do not have the number of the document but its content (for example, tables, in alphanumeric printout).

Results

The development of a closed automated system for collection, primary processing, analysis, storage, retrieval and propagation of scientific data from expeditions of the AANII is going forward in two stages. In the first stage, individual technical complexes and their software are being put together in the form of subprograms which realize various algorithms of primary processing and retrieval which then are combined into a single system for a controlled program.

In the second stage, one of the principal tasks of the BKVTs will be the coordination and control of the experiments on the AANII expeditions and the development of a closed automated system for collection and analysis of scientific data. This center must be equipped, in addition to a computer, with supplementary equipment that is necessary for the organization of a continuous process: primary processing, analysis, recording on DNI, printout and production of data on a technical carrier. In this case, it is possible to develop an information-reference bank which will satisfy current needs. /42

Preparatory work which consists in the development of a descriptor dictionary (systematization and encoding of the data), necessary for the development of an information retrieval system, must be begun without waiting for the development of a corresponding technical base.

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N75 13442

# A SYSTEM OF AUTOMATED PROCESSING OF DEEP WATER HYDROLOGICAL INFORMATION

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Equipping scientific research vessels with computers will allow automated processing of data from direct observations, an important and necessary feature of the conduct of oceanological experiments at sea. The logical and computing capacity of a computer make it possible to automate both the process of handling and the scientific analysis of the results of measurements, considerably reducing the use of inefficient manual labor, simultaneously increasing the quality and efficiency of the calculations.

The most advantageous solution to the problem at hand consists in a ship data measurement complex which allows conversion of the data which are obtained into a convenient form for direct inputting into a computer for the purpose of subsequent automatic processing of the results of the measurements [1- 4, 15]. This approach allows complete solution of the problem.

On this level, the Arctic and Antarctic Scientific Research Institute has been conducting work on the development of an automated system for the collection and processing of scientific data aboard the vessels of the GUGMS, equipped with computers of the "Minsk-22" variety [5, 8]. However, mass production of such measurement complexes containing computers is not a reality and the nature of the raw oceanological data at the present time does not lend itself to total automation of the process. Nevertheless, automation of the processing function is considered advantageous, since it is not anticipated that there will be any apparatus developed that will use manual punching of data for inputting into the computer. The point of view expressed in this paper is supported by the results of investigations [6, 7, 16, 17, 22].

It should be pointed out that insufficient attention has been paid thus far to the problems of primary processing of oceanological data for translation into computers. The results of first efforts in this direction [7, 16, 17] as well as subsequent studies, [2, 3], show how complicated it would be to computerize existing methods and algorithms for manual processing. Some papers [8, 16, 17] have shown that automation of /44
primary processing in the broad sense of the term is outgrowing the limits of the technical problem, becoming a problem which is scientific and whose optimum solution requires performance of special studies.

The primary processing programs described in [16, 17] solve a number of problems having to do with the inputting of the raw oceanological data into the computer (punching system, details of encoding), representation of the data in the memory of the computer, calculations and the carrying out of various corrections in the readings of the sensors, calculation of the standard parameters and finally the nature of the representation of the data at the output of the computer--printing the TGM-3 tables. Nevertheless, some problems on the scientific and methodological level seem to us to be insoluble. For example, in order to standardize levels and interpolate measured quantities, the configuration of the cable and the law of vertical distribution of hydrological elements are approximated by linear and logarithmic relations respectively. In reality, such a representation of the parameters is rarely encountered, which imposes certain limitations on the use of these programs in practice. An approximate method of calculation of the true depth of thermohydrobarometers is employed, inasmuch as values that have been averaged for the layers of the North Atlantic Ocean are used for the density of a column of water extending from the surface of the ocean to the depth to which the thermohydrobarometer has been submerged (climatological value $\alpha_m$) and the actual distribution of water density at the time of submersion is not taken into account. The suggested system is not optimum and when programs are being carried out there is a certain amount of manual labor that is still involved [17]. Such stages in processing as adoption of solutions to the problem of choosing the values of temperature and depth on a level in the case of differences in the readings of the thermometers greater than the permissible value, as well as the calculation of the oxygen content and pH are not solved on the computer and require intervention of the observer. Finally, the program makes inefficient use of the working memory of the computer, so that it is frequently necessary to refer to the magnetic tape, and this considerably increases the use of machine time (up to 40 minutes for calculating one TGM-3 table and several parameters). Experience in using the programs [16, 17] aboard the SRV "Professor Vize" in 1968 and 1970 revealed certain shortcomings which practically exclude the possibility of their efficient use to replace manual compilation of the TGM-3 tables.

In view of the necessity for further improvement of the algorithm for the purpose of total exclusion of manual labor, increasing objectivity and the quality of the calculations, studies were continued to develop reliable methods of processing oceanological data on the computer.

In the following, we shall discuss an automated system for primary

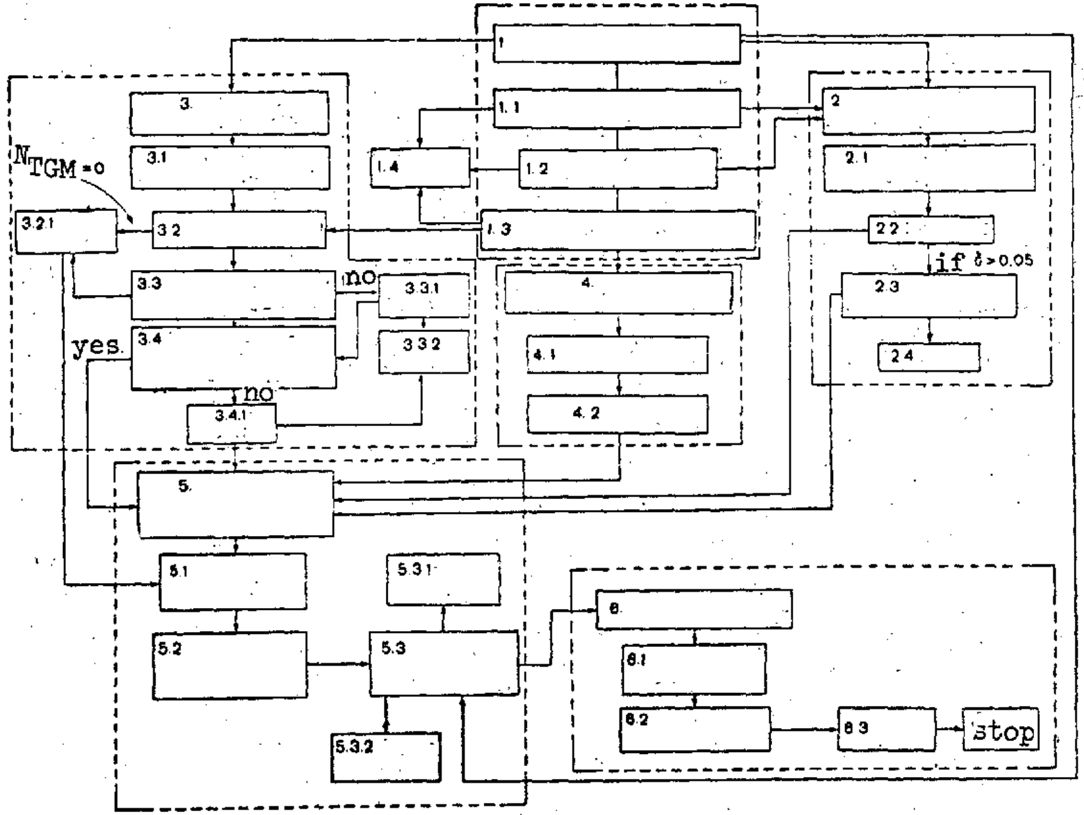


Figure 1--Block diagram of the system for processing oceanological information on the "Minsk-22" Computer. 1 - input of raw data; 1.1 - auxiliary data; 1.2 - readings: TM, TGM; 1.3 - hydrochemical data; 1.4 - printout; 2 - processing of data on temperature; 2.1 - choice, calculation and inputting of TM corrections; 2.2 - calculation of $T_\omega$; 2.3 - Calculation of Ti and choice of temperature; 2.4 - printout; 3 - processing of data on depth; 3.1 - selection, calculation and inputting of corrections of TGM; 3.2 - calculation of N on the basis of TGM; 3.2.1 - calculation of N on the basis of $\alpha_T$; 3.3 - checking the condition $|N_L - N_R| \leq E$; 3.3.1 - calculation of $N_1$; 3.3.2 - printout; 3.4 - checking the condition $\frac{\Delta l}{\Delta N} > 1$; 3.4.1 - calculation of N ; 4 - calculation of hydrochemical elements; 4.1 - S%, $O_2$, pH, Alk; 4.2 - p.Si N; 5 - calculation of parameters, generalization of results; 5.1 - formation of the array; 5.2 - interpolation for standard levels; 5.3 - calculation of $\sigma_T$, $Z_T$ Printout TGM-3; 5.3.1 - printout radiogram; 5.3.2 - output, graphic; 6 - calculations according to methods; 6.1 - vertical stability; 6.2 - dynamic method; 6.3 - printout.

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and scientific analysis of bathometric data. The system carries out the basic stages of primary processing of observations on a drifting station prior to the printing of the final results in the form of a standard TGM-3 table and performs the calculations of the parameters of the vertical stability of the layers in the sea, as well as their dynamic depths and heights which are widely used for subsequent scientific analysis. Primary processing is understood to be not only the inputting of corrections in the readings of the sensors in order to obtain true values, but the entire complex of operations, including interpolation and smoothing, choice of particular points and layers, critical analysis of the reliability of data, and so on [8]. Such complicated elements of analysis as critical analysis, choice of particular points, etc. require special studies and will only be dealt with in part in this paper. /46

The programs discussed here were compiled using the autocode language "Inzhener" (AKI-400 Translator). A block diagram of the system shown in Figure 1 may be conditionally divided into four component parts, each of which carries out an independent stage of process.

## Input of Raw Data

In order to add raw data to the memory of the computer, there are three input blocks which are employed (1.1; 1.2; 1.3). Data prepared for calculations in accordance with the requirements of the machine code are entered on a punched tape and fed into the computer. Initially it is the auxiliary information which is gathered, characterizing the observation conditions (information on the sea, vessel, expedition, number of the station, date of performance of the work, hydrometeorological data), information on the certificates of the devices employed (volumes of deep water thermometers (TM) and thermohydrobarometers (TGM), the volume of the oxygen bottles, main values of the scales on the burettes and thermometers, the coefficient of the block counter, numerical coefficients for the biogens, etc.), then the hydrological information (slope angle of the cable for each level --the length of cable extended, readings of the basic and auxiliary thermometers and thermohydrobarometers, etc.) and the hydrochemical information (the values on the scales of the burettes, colorimeters, etc.). The data from block 1.2 and partly from 1.1 are entered once in the computer and constitute the catalogue of constant characteristics which are only corrected later on as certain data change (for example, replacement of thermometers).

For the purpose of determining the errors in punching and inputting of raw data, a provision is made (block 1.4) for narrow-format check printout (high-speed printer) of certificate data, as well as alphanumeric printout of the deep water hydrological and hydrochemical data in the form of a modified version of the observation logs KGM-6, 9, 10, 11, 12, 21. The mock logs contain only data that is of informational value, and which cannot be recovered if lost. Calculated data, correction values, corrected values for the elements and so on are missing. This method makes it possible to do away with tedious filling in of the logs by hand and guarantees reliable original data.

Following the inputting comes the process of formation of three arrays of data in the memory of the computer to be used in further processing.

## Processing of Information on Water Temperature

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In order to process data on water temperature, blocks 2.1, 2.2, 2.3 and 2.4, shown in Figure 1, have been provided. Block 2.1 performs the selection, calculation, introduction of instrument and reduction corrections in the readings of the thermometers.

For this purpose, from the certificates stored in the memory of the computer, in accordance with the number assigned to the pair of thermometers, main values are selected for the thermometer scale ($Y_j$, j+1), values for instrument corrections ($x_j$,j+1) (j = the initial value on the scale).

The value of the instrument correction for a given calculation is reckoned by linear interpolation of the values at two adjacent junctions

$$k_1 = \frac{(x_{j+1} - x_j)(T - y_j)}{(y_{j+1} - y_j)}, \quad y_j \leqslant T \leqslant y_{j+1}, \tag{1}$$

where $k_1$ is the instrument correction of the thermometer and T is the reading of the thermometer.

The reduction correction $k_2$ is calculated on the basis of a conventional formula [10].

Both corrections are made in the temperature values on the basis of the readings of the ($T_l$) and ($T_r$) thermometers. After making the calculations, when the following condition is satisfied,

$$|T_1 - T_r| = \delta \leqslant 0^\circ.05 \tag{2}$$

the value of the temperature at a given level $T_\omega$ is calculated in block 2.2 according to the formula

$$T_\omega = \frac{T_1 + T_r}{2}. \tag{3}$$

Otherwise, in order to determine the true value of the temperature at level i, the value of the probable temperature $T_i$ is employed which was obtained in block 2.3 on the basis of the temperature values at two superjacent and two subjacent levels by means of the Langrangian interpolation polynomial:

$$T_i = L_n(H) = \sum_{k=0}^{n} T_k L_n^{(k)}(H), \tag{4}$$

where $T_k$ is the temperature value $T_{i-2}$, $T_{i-1}$, $T_{i+1}$, $T_{i+2}$ at two superjacent and two subjacent levels; /48

$L_n^{(k)}(H)$ is the fundamental polynomial for the sequence of junctions (levels) $H_{i-2}$, $H_{i-1}$, $H_{i+1}$, $H_{i+2}$. As the true value of the temperature at a given level, we use the reading of that thermometer whose deviation from the probable temperature is minimal:

$$|T_i - T_{1,r}| = min \tag{5}$$

The number of the bathometer and the readings of the thermometers which do not satisfy conditon (2) are printed on a narrow printout (high-speed printer).

The proposed solution to the problem of the choice of the true temperature at a level with a difference in the readings of the thermometers which is greater than the permissible amount is borrowed from the experience gained in manual processing of the data. In addition, the polynomial approximation of the vertical distribution of the water temperature is the most exact and correct one [14, 21]. Sometimes another approach is used [19], which consists in processing the first readings of the thermometers if condition (2) is satisfied as far as they are concerned. However, in the case of a great difference between the temperature of the water and that of the air, the second and first readings may differ markedly. Consequently, in processing the first reading, one can obtain data which differ from the vertical profile of the water temperature. In addition, for this kind of processing it is necessary to double the amount of data put into the computer which complicates the distribution of the memory and consequently the calculations.

## Processing Data on Depth

This stage consists in the processing of the readings of thermohydrobarometers and calculating the true depth to which the bathometers were submerged. In Figure 1, it is represented by the blocks numbered 3.1, 3.2, 3.2.1, 3.3, 3.3.1, 3.3.2, 3.4, and 3.4.1.

The selection and inputting of the instrument corrections in the calculations of the basic and auxiliary thermometers of the thermohydrobarometers is carried out in block 3.1 in accordance with (1). The reduction correction $k'_2$ is calculated according to [10, 19].

Having obtained the true temperature in block 3.2, the depth to which the thermohydrobarometer was submerged is determined as follows:

$$H = \frac{10\,(T_1 - T_2)\,\alpha_m}{\beta}, \qquad (6)$$

where $T_1$ is the corrected value of the temperature according to the readings of the thermohydrobarometer

$T_2$ is the corrected value of the temperature according to the thermometer readings and

$\beta$ is the coefficient of compressibility of the thermohydrobarometer;

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$\alpha_m = \frac{1}{H_i}\int_0^{H_i} \alpha_i dH$ is the weighted mean average specific volume of water from the surface to the i-TH level

$$\alpha_i = \alpha_{ptS} = V_t(1 - H_i\mu 10^{-9}), \tag{7}$$

where $\alpha_{pts}$ is the specific volume in situ;

$\mu$ is the average coefficient of compressibility of the water from the surface of the ocean of the ith level;

$V_t = \frac{1000}{\sigma_t + 1000}$ is the conditional specific volume ($\sigma_t$ is the conditional density).

The approximate depth of level i is determined by the equation

$$H_i = l_i \cos \alpha_\tau \tag{8}$$

where $l_i$ is the length of the cable down to level i and

$\alpha_\tau$ is the slope angle of the cable.

The calculated depth values on the basis of the readings of the ($H_1$) and ($H_r$) thermohydrobarometers are analyzed for the permissible deviation (block 3.3) in accordance with the criterion

$$|H_1 - H_r| \leqslant \varepsilon, \tag{9}$$

where $\varepsilon$ is the relative value of error in determining the depth, selected according to [19].

In the case of satisfaction of inequality (9), the depth to which the bathometer was submerged is calculated as follows

$$H_\omega = \frac{H_1 + H_r}{2} \tag{10}$$

and the equation is entered in block 3.4.

Otherwise, block 3.3.1 is used to calculate the probable depth $H_i$ by means of the Lagrangian polynomial:

$$H_\omega = L_n(x) = \sum_{k=0}^{n} H_k L_n^{(k)}(x), \tag{11}$$

where $H_k$ is the value of the depth $H_0, H_1, \ldots H_n$;

$n \leq 6$ is the number of thermohydrobarometers;

$L_n^{(k)}(x)$ is the fundamental polynomial for the sequence of junctions $L_0$, $L_1 \ldots L_n$;

For further analysis, use is made of a depth which is calculated by the readings of a thermohydrobarometer in which the deviation from the calculated $H_i$ does not exceed the value

$$|H_i - H_{\mathrm{\Pi},\mathrm{r}}| \leqslant \varepsilon. \qquad (12)$$

The number of thermohydrobarometers for which condition (9) is not satisfied and the depth value adopted are expressed on the BPM.

If the difference between the readings of the thermohydrobarometers is in excess of the value allowed at all horizons, the calculation of the depth is carried out on the basis of the slope angle of the cable in accordance with expression (8) in block 3.2.1. /50

In block 3.4, correction is made for the values of the depth to which the bathometers are submerged:

$$\frac{l_{i+1} - l_i}{H_{i+1} - H_i} = \frac{\Delta l}{\Delta H} > 1. \qquad (13)$$

If the increase in the length of the cable between two adjacent levels ($\Delta L$) is greater than the increase in depth according to the readings of the thermohydrobarometers at these levels ($\Delta H$), the calculated values for depths that have been checked in equation (9) are adopted as the true ones and the performance of further calculations is in accordance with block 5. Otherwise, the readings of the thermohydrobarometer on the ith level are discarded and the calculation of the true depth of submersion of the bathometers is conducted in accordance with expression (12) in block 3.4.1 with subsequent transferral of the equations to block 5.

## Calculation of Hydrochemical Elements

This stage is shown in Figure 1 by two blocks, 4.1 and 4.2. All of the calculations are carried out in the following order.

1. Calculation of the salinity is performed in accordance with the standard system. At a certain value of chlorine content, a correction is made in the reading of the burette when titrating the sample. Therefore, according to the Knudsen formula [10], the salinity (S) in percent is calculated as follows:

$$S = 0.03 + 1.805\ Cl. \tag{14}$$

The oxygen content ($O_2$, 2 ml per liter) is determined according to the formula given in [18]:

$$O_2 = \frac{111{,}96\,(n_0 + k_0)\,k_g}{v - 2}, \tag{15}$$

where $n_0$ is the reading of the burette

$k_0$ is the calibration correction

$k_g$ is the correction coefficient for the hyposulfite solution

v-2 is the volume of the oxygen bottle assuming that 2 mm of the agents have been added.

The solubility of the oxygen in sea water is determined according to the formula

$$O_2' = \frac{1}{1{,}4929}\left[14{,}161 - 0.3943T_\omega + 0{,}007714T_\omega^2 - 0{,}646\cdot 10^{-4}T_\omega^3 - \right.$$
$$\left. - S\left(0.0841 - 2{,}56\cdot 10^{3}T_\omega + 3.71\cdot 10^{-5}T_\omega^2\right)\right]. \tag{16}$$

Likewise, known formulas are used to calculate the oxygen content in percentage and microgram-atoms per liter [18].

3. Determination of the concentration of active hydrogen ions (pH) is performed in accordance with the following formulas taken from [18]:

$$pH_C = pH_O + \Delta pH_S + \Delta pH_t + 2\,(t_C - T_\omega) + \gamma\,(t_\omega' - T_\omega); \tag{17}$$

$$pH_0 = pH_O + \gamma T_\omega; \tag{18}$$

where $pH_c$ is the calculated pH value;

$pH_o$ is the observed pH value;

$\Delta pH_S$ is the saline correction which is a function of the degree of salinity;

$\Delta pH_t$ is the correction for scale values which is a function of the value of $T_c$;

$\alpha$ is the temperature coefficient for the change in $pH_c$ as a function of the indicator;

$t_c$ is the scale temperature;

$t'_\omega$ is the temperature of the sample at the time the pH is determined;

$T_\omega$ is the temperature of the sample in situ;

$pH_0$ is the concentration of active hydrogen ions at 0°;

$\gamma$ is a coefficient which is determined according to the formula;

$$\gamma = \frac{pH_o - 5}{300}. \tag{19}$$

4. The alkalinity content (Alk) at the observed horizons is converted from micrograms per liter to microgram-equivalents per liter:

$$\mathrm{Alk}\,\frac{\mu g\cdot eq}{liter} = \mathrm{Alk}\,\frac{\mu g}{liter}\cdot Q$$

where Q is the numerical coefficient from the catalog of constant characteristics.

For other trace elements: phosphates (Pn), silicone (Si), nitrates and nitrites (N), the values of the calorimeter are converted from micrograms per liter to microgram-atoms per liter:

$$P_n\,\frac{\mu g\cdot a}{liter} = P_n\,\frac{\mu g}{liter}\cdot Q_1;$$

$$S_i\,\frac{\mu g\cdot a}{liter} = S_i\,\frac{\mu g}{liter}\cdot Q_2;$$

$$N\,\frac{\mu g\cdot a}{liter} = N\,\frac{\mu g}{liter}\cdot Q_3.$$

## Calculation of Oceanological Parameters, Generalization of the Final Result

This stage consists in the determination of certain parameters at standard levels and generalization of the final results of the calculations in a form which is used in practice and regular analyses. It consists of a group of calculations involving /52 primary processing. All of the operations are carried out in blocks 5.1, 5.2, 5.3, 5.3.1, 5.3.2. After determining the true depths of submersion of the bathometers and the values of the elements, the necessary data are placed in block 5.1, where formation of an array is carried out according to the observations of the levels. For this purpose, information is used from blocks 2.2, 2.3, 3.2.1, 3.4, 3.4.1, 4.1 and 4.2.

In view of the necessity of representing the values of the elements and the parameters on the standard levels in block 5.2, polynomial interpolation of the values of the temperature, salinity and oxygen content are carried out on the specified levels by means of the following polynomial

$$L_3(H) = \sum_{k=0}^{3} y_k L_3^{(4)}(H), \tag{20}$$

where $L_3(H)$ is the value of the element at the standard level;

$y_k$ is the value of the element being interpolated on two superjacent and two subjacent level;

$L_3^{(4)}(H)$ is the fundamental third degree polynomial for four successive junctions $H_{i-1}$, $H_{i-2}$, $H_{i+1}$, $H_{i+2}$.

On the basis of the values obtained for the temperature, salinity, and oxygen content, the values of the conditional density, conditional specific volume, oxygen content in percent and in microgram-atoms per liter at standard levels are calculated. The remaining chemical elements are determined only on the basis of the measured levels, so that the question of the vertical distribution of the hydrogen index, alkalinity and biogenic elements has been studied insufficiently and the use of any of the existing methods of interpolation may be questioned.

Later along in the process of data evaluation is the stage of generalization of the results of the direct observation in a form which is convenient for its subsequent use.

In block 5.3, in the alphanumeric printer (ATsPU), the oceanological and hydrometeorological data are put out in the form of a standard TGM-3 table. Thus far, the latter is the principal output material of scientific research vessels, and is used directly in regular analyses and is suitable for archival storage. The headline and last graph of the table are printed including data from the block in stage 1.

For the purpose of a functional control of the quality and the analysis of the data which are obtained, automatic plotting of the graphs of the vertical distribution of temperature, salinity and water density is performed, as well as the "T-S" curves on the "Neva" facsimile machine, whose resolution is an order of magnitude higher than that of the ATsPU, making it possible to increase the accuracy of the graphic representation of the data to 0.02-0.03 degree or a thousandth. For transmission to the data collection centers, a radiogram is printed on the ATsPU in accordance with the KN-05 code which contains data on the temperature and salinity at standard levels down to a depth of 1,000 meters.

This ends the stage of primary processing of oceanological data on the "Minsk-22" computer. /53

Calculations According to Methods

The effective usage of the data that is fed to the computer memory requires that the volume of computations not be limited merely to the primary processing. The basic task of the computer is the solution of diverse analytical problems and the execution of model calculations that govern the scientific analysis and investigation of oceanological conditions. For this purpose, the system includes programs for computing the vertical stability of the layers in the sea and certain parameters in accordance with the dynamic method of computing the elements of marine current. Calculations according to these methods are carried out in blocks 6.1 and 6.2. The basis for the calculation of the vertical stability E is the familiar Hesselberg-Sverdrup expression [12, 13]:

$$E = \frac{\partial \rho}{\partial T}\left(\frac{dT}{dH} - \frac{d\theta}{dH}\right) + \frac{\partial \rho}{\partial S}\frac{dS}{dH}, \qquad (21)$$

where $\rho$ is the density of the water;
$\zeta$ is the potential temperature.

Determination of the parameters according to the dynamic method is carried out up to the stage of calculation of the dynamic depths and altitudes according to [11]:

$$D=\int_{H_0}^{H_i}\alpha dH,\quad d=\int_{H_i}^{H_0}\alpha dH, \tag{22}$$

where D is the dynamic depth;
d is the dynamic altitude;
$\alpha$ is the specific volume.

The methodological aspect of the these calculations has been discussed in detail in many papers [11, 12, 13].

These subprograms include the system of processing deep-water oceanological data on the "Minsk-22" computer on the basis of data from observations from an individual drifting station.

This technology for automated processing was successfully tested on the fourth through sixth voyages of the scientific research vessel "Professor Zubov". Tables 1-2 show the results of the comparative analysis of the accuracy of the processing of the observations manually and on a computer at 119 stations, carried out at depths from 142 to 4314 meters. The number of thermohydrobarometers in the series varied from 1 to 7. Table 1 shows the estimates of the accuracy of the calcula- /54 tion of the depth and temperature at the measured levels in accordance with expressions (3) and (6). Interpolated data were not used in the calculations. Table 2 shows estimates of the accuracy of the data with respect to depth, temperature, salinity, as obtained through interpolation according to the Lagrangian polynomial. This analysis indicates that the deviations of these depths in 89.3% of the cases are not in excess of ±2 meters, while the temperatures in 97.5% of the cases are within ±0.02°. The errors in the interpolation of the data on depth are not in excess of ±4 meters in 93.7% of the cases, in 87.6% of the cases the temperature is within ±0.04°, and in 97.2% of the cases the salinity is within ±0.02%. More significant variations have to do with the subjective nature of manual processing in events of unsatisfactory functioning of thermometers and thermohydrobarometers. The results obtained satisfy the /55 requirements for accuracy in processing of deep water observations and guarantee high quality of the initial information. This was made possible by automation of the compilation of the TGM-3 tables aboard the research vessel "Professor Zubov," beginning with the fifth voyage (May 1970).

Let us determine the effectiveness of using the computer for these purposes. Primary processing of the data from a single station by hand at a depth of about 3,000 meters requires 5 to 6 hours. Punching the raw data for machine processing consumes an average of 30-40 minutes, and computation on the computer takes up 5-7 minutes. Consequently, the effect of using a computer for processing the data from one station can be reckoned at 4.5-5.5 hours, while the efficiency of the calculations increases by an order of magnitude.

The effect of introducing the entire system is considerably in excess of the input data, inasmuch as the latter do not include the expenditure of manual labor for scientific evaluation. The increase in the objectivity of the calculations is not insignificant, but this factor cannot be measured in numbers.

The above-described system for automated processing of oceanological data is basically used aboard scientific research vessels that are equipped with the "MINSK-22" computer. However, the experience we have with the processing of expedition materials at the coastal coordinating-computer center, to which it is sent either by radio [7] or in the form of punched cards after the expedition is over [20], as well as the results of an experiment that was conducted by a fellow-worker at the Arctic and Antarctic Scientific Research Institute, F.M. Pryamikov, in 1970 aboard the expeditionary vessel "Shtorm," indicate the advisibility of adopting this technological arrangement aboard research vessels that are not equipped with computers. In this case, the results of the observations are entered on punched tape aboard ship during the voyage and the tape is then sent to the BKVTs. The form and content of the processing are essentially determined by the specialization of the research vessel and the physical-geographical characteristics of the region being studied. The specific aspects of the utilization of such vessels in the shallow Arctic seas (low efficiency of utilization of thermohydrobarometers effective transmission of processed materials from observations from the surface to the bottom to the staff of the marine operations) renders it unnecessary to use this system to the full. In this case, the introduction of correction in the temperature and salinity values, analysis of the thermohydrobarometers and calculations according to the dynamic methods are all dropped. However, the basic principles of automated processing and analysis on board ships equipped or not equipped with computers do not show any fundamental differences.

This system of programs makes it possible at the present time

TABLE I EVALUATION OF THE ACCURACY OF CALCULATION OF THE DEPTH AND TEMPERATURE OF THE WATER AT THE MEASURED HORIZONS

| $H$ | | | $T_\omega$ | | |
|---|---|---|---|---|---|
| $\Delta H$, m | number of cases | % | $\Delta T_\omega$, °C | number of cases | % |
| 0 | 52 | 37,1 | 0 | 150 | 29.1 |
| ±1 | 48 | 34.3 | ±0,01 | 313 | 60,7 |
| ±2 | 25 | 17,9 | ±0,02 | 40 | 7,7 |
| ±3 | 5 | 3.6 | ±0.03 | 9 | 1,7 |
| ±4 | 1 | 0,7 | ±0,04 | 1 | 0,2 |
| ±5 | 2 | 1.4 | ±0.05 | 3 | 0,6 |
| ±6–10 | 1 | 0,7 | | | |
| ±11–20 | 6 | 4,3 | | | |

Note: Total number of cases H=140; $T_\omega$=516.

TABLE II EVALUATION OF THE ACCURACY OF INTERPOLATION OF THE DATA ON DEPTH, TEMPERATURE AND SALINITY

| $H$ | | | $T$ | | | $S$ | | |
|---|---|---|---|---|---|---|---|---|
| $\Delta H$, m | number of cases | % | $\Delta T$, °C | number of cases | % | $\Delta S$, ‰ | number of cases | % |
| 0 | 535 | 291 | 0 | 340 | 22,7 | 0 | 1279 | 85,7 |
| ±1 | 747 | 407 | ±0,01 | 617 | 41,2 | ±0,01 | 161 | 10. |
| ±2 | 167 | 9.1 | ±0,02 | 322 | 21,9 | ±0,02 | 10 | 0,8 |
| ±3 | 171 | 9,3 | ±0,03 | 26 | 1,7 | ±0.1–0.2 | 42 | 278 |
| ±4 | 100 | 5,5 | | | | | | |
| ±5–10 | 84 | 4,6 | ±0.04 | 2 | 0,1 | | | |
| ±10–20 | 30 | 1.6 | ±0,05–0,1 | 185 | 12,4 | | | |
| >20 | 2 | 0,1 | | | | | | |

Note: Total number of cases H = 1722; $T_\omega$ = 1492; S = 1492.

to automate the basic stages of both primary and scientific processing of oceanological information which has been obtained in the course of operation of drifting stations. Nevertheless, in the course of the development on the computer of this automated system for processing, a number of problems of a practical and theoretical nature arose which did not lend themselves to final solution. Algorithmization of the process of primary processing by observing the analogy with manual procedures is complicated by the presence of a great many logical operations and a shortage of basic quantitative criteria that are necessary for adoption of a final solution. For example, it is necessary to refine our concepts concerning the vertical distribution of various oceanological elements and parameters. The utilization in oceanological research of low-inertia apparatus has made it possible to obtain data which cast doubt on the continuance and monotonic nature of the distribution of various properties of the state of seawater [21]. The complexity of the function which adequately expresses the relationship between the temperature and salinity of the water and the depth makes it possible to consider that even the most accurate interpolation of parameters with respect to the vertical is insufficiently founded. /56

It is necessary to refine the configuration of the table in the case of deep water observations. Due to the widely used method of operation of the vessel at large slope angles, the shape of the cable and the surface layer may differ significantly from the theoretical (parabola, catenary). There are no reliable criteria for determining the layer in which there is a density jump (a break in the density profile), which is determined by the significant gradients in temperature and salinity in the active layer. For such cases, the polynomial approximation of the distribution of elements with respect to the vertical cannot be considered admissible. The extrapolation of the depth is also complicated if thermohydrobarometers are not used or function unsatisfactorily at levels below 1,000-1,500 meters. Criteria (2) for obtaining the true value of the water temperature at the horizon are considered insufficiently founded.

Successful development of an algorithm for primary processing of information on the computer goes beyond the limits of the ordinary technical problems and cannot be carried out without performing special studies. Only a detailed scientific analysis of the data from observations will make it possible to determine the characteristics of the real and multifactorial medium which remains disregarded in manual processing. An important role in this regard is played by critical analysis of the reliability of the raw data, one of whose varieties can be the method of mathematical statistics (evaluation of the reliability of the zero hypothesis). For this purpose it is necessary to plot typical curves of the vertical profiles of various elements and their reliability limits for quasiuniform regions and periods of the year. In evaluating the reliability limits it is necessary to take into account the law of distribution and the coherence of the analyzed elements in space and time. The results of a comparisor of typical and observed curves allows an objective approach to the evaluation of the quality of the raw data for the purpose of an appropriate elimination of erroneous values and checking the given method of approximation of the data.

The system for analyzing the data on the computer at the present time has been developed only as far as deep water data is concerned. However, oceanological information is not exhausted by the material from bathometric observations and the existing methods of analysis constitute a combination of various recordings and methods of computation. Therefore it is natural to attempt to generalize the principles for further methods of developing systems of analysis and processing of data on computers. /57

The principal factor in the analysis is the separation of the materials obtained into random and conditionally determined components. This separation is possible through filtration of the original series for the purpose of determining processes with given periods (frequencies). As it applies to oceanology, the problem consists in isolating from the total oscillations the tendencies and trends that govern the slow and regular changes in the process and the small scale fluctuations which amount to random noise. The determined changes include long-period tides, seasonal circulation of water, phenomena associated with solar activity, characterizing monthly or seasonal averaging, as well as changes in the mesoscale (from several hours to several days): tidal phenomena (generated by ten basic tidal waves), internal waves, and so on. The basic methods of studying such phenomena--simulation of coastal and oceanic circulation, calculations using the dynamic method, determination of the stability of masses of water, spectral and harmonic analysis and boundary value problems of tides.

An analysis of the random component (noise) includes the study of the microprocesses with insignificant space-time scales. The principal method is the probability statistical investigation with total analysis of time series (the calculation of the momentary characteristics with evaluation of the optimum degree of approximation of the empirical law of distribution to some theoretical law), calculation of the structural and correlational functions, as well as functions of spectral density. The features of the statistical structure are employed for an objective reconstruction of the field at the junctions of some type of network.

In the final stage of analysis of the data on the computer, the problem of the compaction of the data and its recording on the technical carrier in a form that allows subsequent restoration of the multidimensional law of distribution of a parameter is solved. It is necessary to display the final results on a cathode ray tube, coordinating plotting device and digital printout.

At the present time, the development of this system for analysis and processing of oceanological information on a computer to the fullest extent is complicated by the shortage of investigational data on the natural statistical structure of these processes and fields. However, the results of studies that have been conducted and published [1-4, 15, 17], indicate that it is possible to transfer to the computer those basic stages which include filtration and objective analysis.

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# ERROR IN INTERPOLATION AND CHOICE OF THE RANGE OF DISCRETENESS IN MEASUREMENTS IN A HYDROPHYSICAL FIELD

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In the theory of the development of the hydrophysical field, objective or numerical analysis is understood to be the handling and execution of a method which makes it possible to use the data from hydrophysical measurements of the aquatorium of the ocean to reconstruct the values of a hydrophysical element at the junctions of a regular network. This involves the problem of determining the statistical characteristics of the field by working out a discrete realization of the measurements.

The manner of solving the problem of selecting the appropriate moments for performing the measurements, their mutual arrangement and the number of individual measurements determines the results of the averaging, i.e., the results on the statistical structure of the field on which the error in interpolation in turn depends [1]. The method of optimum interpolation is based on the utilization of the theory of linear interpolation of stationary random sequences [2].

Interpolation is carried out observing two conditions:

(1) The determined intermediate value is a linear combination of measured values;

(2) The reconstructed value is determined under the condition of a least mean square of the error of interpolation.

In the case of a limited system of measurements for describing a statistical structure of a field by the method of optimum interpolation, the reconstructed value of deviation F* at the point in question is found by the formula

$$f^* = \sum_{i=1}^{n-1} g_i f_i,$$

where f* is the reconstructed value of the function of the measurements at the point in the field and

$g_i$ are the weight coefficients which reconstruct the values of the field.

The weight coefficients are chosen under the condition that the estimate f* gives the best results of approximation in the mean statistic, i.e., it reduces to a minimum the value of the mean square error in reconstruction $\varepsilon$. /60

The system of linear equations for determining the weights has the form

$$\sum_{j=1}^{n} \mu_{i,j} g_i = \mu_{i,0},$$

where $\mu_{i,0}$ are the values of the normal correlation function for distances between the stations and the point of interpolation.

Then the error in interpolation will be determined by the formula

$$\varepsilon = 1 - \sum_{i=1}^{n} \mu_{i,0} g_i. \quad (1)$$

Hence the measure of the error of interpolation is determined essentially by the covariational matrix $[\mu_{i,j}]$ (i, j = 1, 2, 3) which in turn is determined completely by the geometry of the arrangement and the discreteness of the measurements.

$$\begin{pmatrix} \mu_{11}\mu_{12}\dots\mu_{1n}\mu_{10} \\ \mu_{21}\mu_{22}\dots\mu_{2n}\mu_{20} \\ \mu_{n1}\mu_{n2}\dots\mu_{nn}\mu_{n0} \end{pmatrix} = \{\mu_{i,j}\}$$

$$\mu_{i,j} = \mu(r_{i,j}),$$

$$r_{i,j} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}.$$

The most rational approach is the location of the measurements (stations) at the points of a lattice formed by equilateral triangles.

Discreteness of measurement is understood to be the determination of the distance between the station, where the error $\varepsilon$ does not exceed a given value. The solution of this problem is very complex. However, if we use interpolation, not for the entire combination of measurements in an investigated space but on the basis of adjacent measurements (2, 3, 4 etc.) we can obtain relatively simple formulas for its solution.

Assume that the individual measurements of a given realization in a field $f_k$ ($k = 1 \ldots, n$), having a continuous normal correlation function $\mu(\tau)$ are known.

We will determine the reconstructed value $f^*$ as a combination of measurements spaced over the interval T with weight coefficients which insure that minimum of the mean square in accordance with formula (1).

Let us determine the approximate value $f^*(\theta)$ of the given realization with $x + \theta$ as the linear combination of the calculations of $f_k$ and $f_{k+1}$ with coefficients which insure the minimum of the mean square of the value $f(x+\theta)-f^*(\theta)$ We will then have [2]:

$$f^*(\theta) = g(\theta) f_k + g(\tau - \theta) f_{k+1};$$

$$\varepsilon = \frac{1}{\sigma^2} \overline{[f(x+\theta) - f^*(\theta)]^2} = [1 - F(\theta) - F(\tau - \theta)];$$

$$g(\theta) = \frac{\mu(\theta) - \mu(\tau - \theta)\mu(\tau)}{1 + \mu^2(\tau)};$$

$$F(\theta) = \mu(\theta) g(\theta). \tag{2}$$

In this case, the covariational matrix will have the form /61

$$\begin{pmatrix} 1 & \mu(\tau) & \mu(\theta) \\ \mu(\tau) & 1 & \mu(\tau - \theta) \end{pmatrix} (\tau = T).$$

It follows from (2) that $\varepsilon(\theta) = \varepsilon(T) = 0$, i.e., $\varepsilon(\theta)$ must pass through 0 at $0 < \theta < T$ and reach a maximum at $\theta = \frac{T}{2}$, equal to

$$\varepsilon_{\max} = 1 - \frac{2\mu^2\left(\frac{T}{2}\right)}{1 + \mu(T)}.$$

Hence the scatter of the approximate value around the approximator does not exceed $\varepsilon_{max}$, determined by expression (3). Without adding the intermediate calculations, we can obtain analogous equations for the case of location of stations at the vertices of an equilateral triangle with an interval between stations T (interpolation is carried out on the basis of three measurements):

$$\varepsilon_{max} = 1 - \frac{3\mu^2\left(\frac{T}{\sqrt{3}}\right)}{1 + 2\mu(T)}.$$

Let us examine a case when we have four observations of stations that are located at the corners of a square. In accordance with formula (1), the error in interpolation for this case will have the form

$$\varepsilon = 1 - \sum_{i=1}^{4} \mu_{i,0} g_i. \tag{4}$$

The standard procedure of differentiating an expression for error and finding the point at which the derivative vanishes can be used to show that the error reaches its maximum at the center of the square. /62

Considering this fact to be known, we can obtain the weight coefficient for interpolation at the center of the square

$$g_i = \frac{\mu\left(\frac{T}{\sqrt{2}}\right)}{1 + \mu\left(\frac{T}{\sqrt{2}}\right) + 2\mu(T)} \quad (i = 1, 2, 3, 4).$$

Substituting $g_i$ in expression (4), we obtain the maximum error of the optimum interpolation for the square

$$\varepsilon_{max} = 1 - \frac{4\mu^2\left(\frac{T}{\sqrt{2}}\right)}{1 + \mu\left(\frac{T}{\sqrt{2}}\right) + 2\mu(T)}. \tag{5}$$

Practically speaking, it makes sense to choose T so that $\varepsilon_{max}$ is much less than one.

Let us simplify (5) by taking into account the small size of T relative to the extent of the aquatorium in question.

Let us expand $\mu$ (T) into a Maclaurin series, which in the general case has the form:

$$\mu(T) = 1 + \mu_1|T| + \mu_2|T|^2 + \ldots + \mu_n|T|^n + R_n(|T|), \tag{6}$$

Where $\mu_i = \frac{1}{i!} \mu^{(i)}(0)$;

$R_n$ is the residual term.

For functions which do not have derivatives at the point T = 0, we will have

$$\mu_i = \frac{1}{i!} \lim_{T \to +0} \mu^{(i)}(T).$$

Let us substitute series (6) in (5), limiting ourselves by cutting off the series at $\mu_5 T^5$, and in the course of the calculations we will discard those terms which contain $\mu_1$ and $T^i$ with $i>2$ (these terms are not principal ones). We will then have

$$\begin{aligned}\varepsilon_{max} = \frac{1}{4}\{\mu_1 \sqrt{2}(\sqrt{2}-3)T + 2\mu 3T^3 + (4\mu_4 - \mu_2^2) + \\ + \sqrt{2}\left[(\sqrt{2}+3)\mu_5 - \mu_2\mu_3\right]T^5\} + 0(\alpha^6).\end{aligned} \tag{7'}$$

Depending on the functions $\mu(T)$ from expression (7') we will obtain three values of $\varepsilon_{max}$:

$$\mu_1 \neq 0 \quad \varepsilon_{max} = \frac{\sqrt{2}(\sqrt{2}-3)}{4}\mu_1 T + 0(\alpha^2);$$

$$\mu_1 = 0,\ \mu_2 \neq 0,\ \mu_3 \neq 0 \quad \varepsilon_{max} = \frac{\mu_3 T^3}{2} + \left(\mu_4 - \frac{\mu_2^2}{4}\right) T^4 + 0(\alpha^5); \tag{7}$$

$$\mu_1 = 0,\ \mu_2 \neq 0\ \mu_3 = 0,\ \mu_4 \neq 0,$$

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$$\varepsilon_{max} = \left(\mu_4 - \frac{\mu_2^2}{4}\right) T^4 + \sqrt{2}(\sqrt{2}+3)\mu_5 T^5 + 0(\alpha^6). \tag{8}$$

It can be shown that these cases describe a sufficiently broad class of continuous functions $\mu(T)$.

Let us change formulas (7) and (8) to a form which is convenient for finding T for a given value of $\varepsilon_{max}$. From (7) we will have

$$\varepsilon_{max} \approx \frac{\mu_3 T^3}{2}\left\{\left[1 + \left(\mu_4 - \frac{\mu_2^2}{4}\right)\frac{2T}{\mu_3}\right]^{1/3}\right\}^3.$$

Let us expand the expression in the brackets in a series which is limited to the first term. Then, after we extract the cube root, we will have the quadratic equation

$$T^2 = \frac{6\mu_3}{4\mu_4 - \mu_2^2} T - \frac{6\mu_3 \sqrt[3]{\varepsilon_{max}\frac{2}{\mu_3}}}{4\mu_4 - \mu_2^2} \approx 0,$$

whose solution gives the desired formula

$$T = \frac{3\mu_3}{4\mu_4 - \mu_2^2}\left(\sqrt{1 + \frac{2(4\mu_4 - \mu_2^2)}{3\mu_3}\sqrt[3]{\varepsilon_{max}\frac{2}{\mu_3}}} - 1\right). \tag{9}$$

From expression (8) we will have

$$\varepsilon_{\max} \approx \frac{T^4\left(4\mu_4-\mu_2^2\right)}{4}\left\{\left[1+\frac{\mu_5\left(\sqrt{2}+3\right)\sqrt{2}T}{\mu_4-\frac{\mu_2^2}{4}}\right]^{1/4}\right\}^4.$$

Similarly, we will have

$$T=\frac{\sqrt{2}\left(\mu_4-\frac{\mu_2^2}{4}\right)}{\left(\sqrt{2}+3\right)\mu_5}\left(\sqrt{1+\frac{\sqrt{2}\left(\sqrt{2}+3\right)\mu_5}{\mu_4-\frac{\mu_2^2}{4}}\sqrt[4]{\varepsilon_{\max}\frac{1}{\mu_4-\frac{\mu_2^2}{4}}}}-1\right). \quad (10)$$

On the basis of equations (9) and (10) which we have obtained, given the value of $\varepsilon_{max}$, we can find T with an error of the same order as the error in the determination of $\varepsilon_{max}$.

If $\mu(T)$ is known, we can find not only $\varepsilon_{max}$ but also can plot the distribution of the error over the area, as was done in Fig. 1, where for the square $\mu(T) = \exp(-0.1\,|T|)$, with $T = 1$, $\varepsilon_{max} = 0.0558$ and for the rhombus $T = \frac{\sqrt{2}}{\sqrt[4]{3}}$.

However, if we calculated using formula (4) we will obtain $\varepsilon_{max} = 0.056$, i.e., a result which is obtained on the basis of approximate formulas and is in good agreement with actual results.

In addition, as we can see from figure 1, the error in interpolation at the center of the rhombus is less than the error in interpolation at the center of the square, although the discreteness of the lattice is less than the discreteness of the square. /64

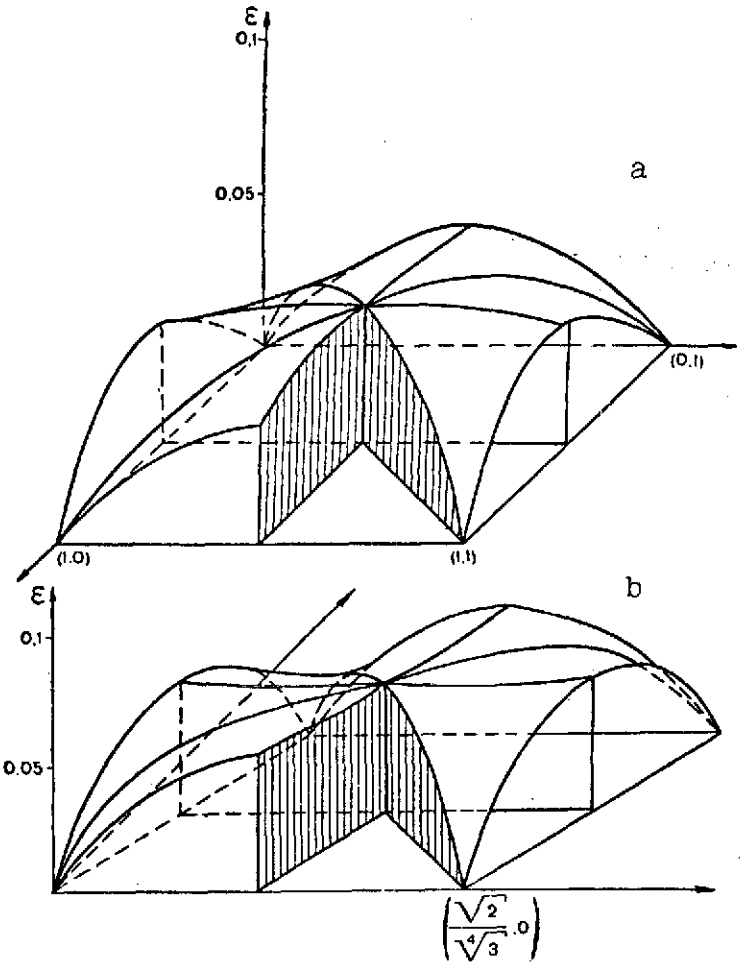


Figure 1--Distribution of the error in interpolation for a square (a) and a rhombus (b).

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# THE PROBLEM OF SELECTING AN OPTIMUM FREQUENCY FOR A MEASURING GENERATOR IN DETERMINING THE VALUE OF THE HYDROPHYSICAL PARAMETER WITH A GIVEN ACCURACY

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In hydrophysical electronic devices that have been developed in recent years, considerable use is made of the frequency method of measurement. The use of this method for the measurement of temperature is based on the employment of a thermistor as the temperature-sensitive element, connected to the circuit of a measuring RC generator for regulating its frequency. /65

This same principle is used in designing the measuring temperature generators of autonomous devices for the measurement of the microstructure in the layer of water adjacent to the surface, included in the SIGMA-s complex. The problem of choosing the optimum frequency for the measuring generator is a timely one and is worthy of further study.

The information theory of measuring devices [1] establishes a fixed relationship between the magnitude of the energy required by the measuring device and the value of the information being transmitted, from which comes the concept of dead time of measuring devices. It has been shown that the dead time of an electronic device is equal to

$$\tau_{\text{м}} = \gamma^2 t_{\text{meas}} = 10^{-8}, \qquad (1)$$

where $\gamma$ is the relative error in measurement and
$t_{\text{meas}}$ is the time during which measurements are carried out.

It should be emphasized that we are talking here only about random errors, since analyzing the signal to reduce them is more time consuming than eliminating the remaining errors

From the concept of the dead time of the measuring device it follows that, with a given accuracy, one can determine unambiguously the length of the measurement time. For the case of temperature measurement in a range from $-2°$ to $+32°$C with an error of no more than 0.01° the total value of $\gamma$ will be approximately equal to $3.10^{-4}$. We will take with a reserve (for consideration of additonal errors due to the unstability of the characteristics of the measuring generator in the range of operating conditons) $\gamma_{random} = 10^{-4}$. Then on the basis of expression (1) $T_{meas}$ will be 1 second.

Due to the fluctuation processes that occur when the amplitude of the signal is changed, measuring RC generators have a final value of instability which is difficult to reduce. We performed measurements of the fluctuation instability of the period of oscillation of a model of a measuring generator by means of the C1-35 oscillograph, extending the period of the oscillation over the entire screen. The range of instability of the period $\gamma_1$ turned out to be between $5 \cdot 10^{-2}$ and $10^{-1}$. /66

In addition, in such generators, in order to convert their frequencies to digital form it is necessary that when the resistance of the thermistor changes the maximum deviation in the frequency $f_m - f_0$, the magnitude of the range ($\Delta$) of the change in the parameter, and the magnitude of the quantum ($\delta$) of the parameter and the measurement time $T_{meas}$ are linked by the relationship

$$t_{meas}(f_m - f_0) = \frac{\Delta}{\delta}, \tag{2}$$

where $f_0$ is the minimum frequency of the generator and
$f_m$ is the maximum frequency of the generator.

The constant component of the generator $f_0$ is excluded in the processing of the signal by means of a calculation of the auxiliary high stability frequency equal to $f_0$. In practice this means that for a given case of temperature measurement with $T_{meas} = 1$ second deviation of the frequency of the measuring generator on the basis of (2) will be 3400 Hz.

When converting the frequency of the measuring generator to digital form (calculating the number of periods in a high stable time interval) one actually carries out a statistical averaging of the length of the period of the oscillations, so that the random error in the measurements is reduced by $\sqrt{\frac{\Delta}{\delta}}$ times, i.e.

$$\gamma_{meas} = \frac{\gamma_1}{\sqrt{\frac{\Delta}{\delta}}}. \tag{3}$$

For the case in question the measurements $\sqrt{\frac{\Delta}{\delta}} \approx 58$, which makes it possible to determine the value of the parameter with an error of $\gamma_{meas}$ approximately $10^{-3}$.

In order to obtain an error of $\gamma_{random} = 10^{-4}$, it is obviously simpler to use the method of statistical averaging of the results of several repeated measurements instead of increasing the stability of the period of oscillations of the generator by using low noise (and costly) electronic components. This complicates the circuit, and is not always possible anyway.

In order to utilize this method of statistical averaging, it will suffice to provide the necessary number of repeated measurements so that the magnitude of the random error can be reduced by a factor of 10 which, according to expression (3), will be equal to 100. Consequently, the design of the measuring generator must be such that it allows maximum deviation of the frequency 100 times greater than the deviation under condition (3), i.e., $(f_m - f_0)_{statistical}$ equals 340 kHz. /67

Let us determine the frequency range of the operation of the measuring generator for the latter case. The coefficient of the change in resistance of the thermistor with changing temperature will be 3-5% per degree. In the range of temperatures measured, ($\Delta = 34°$), in selecting the average value of the indicated coefficient, the relative change in resistance of the thermistor will be

$$\frac{\Delta R_T}{R_T} = 1.36. \tag{4}$$

Since the deviation in the frequency of the variations of the measuring generator is proportional to the change in the value of the time-determining element, taking (5) into account we can determine the minimum frequency

$$f_{0\,statistical} = \frac{(f_m - f_0)_{statistical}}{\frac{\Delta R_T}{R_T}} \tag{5}$$

i.e., $f_{0statistical} = 250$ kHz.

Consequently, the measuring generator must change its frequency from 250 kHz to 590 kHz in a temperature range from -2° to +32°.

We performed measurements of the fluctuational instability of the period of oscillations in a model of a measuring generator by means of a digital frequency meter with averaging of $10^3$ and $10^5$ oscillations. The results of the measurements confirmed the findings that are set forth in the article.

Hence, in choosing the working frequency for a measuring generator it is necessary to proceed on the basis of the requirements for accuracy of the permissible measurement time, taking into account the actually possible stability of the period of the oscillations.

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# SMALL PARAMETRIC MODEL OF THE PRECOMPUTATION OF METEOROLOGICAL FIELDS ON THE BASIS OF COMPLETE EQUATIONS AND ITS ENERGETIC ANALOGS /68

Ye. P. Borisenkov

The problem of constructing small-parametric models for precalculation of hydrometeorological fields, in which the mechanism for conversion of the basic forms of energy is described simultaneously with precalculation of the meteorological elements themselves, was treated in [3, 6, 7, 15, 18]. The energy control in the hydrodynamic models may be good and in fact may be the only physical check of their quality.

It must be pointed out that attempts to use energy control in the mathematical modeling of the circulation of the atmosphere have already been made [10]. However, thus far in the overwhelming majority of models, it is either absent or performed formally to a certain degree. The fact is that including the curve of the kinetic or useful potential energy in the numerical model of the calculation, using principles of retention of certain characteristics, is extremely useful and valuable, but it does not constitute energy control, which is what we are discussing. A simple analysis of the curve of kinetic energy may characterize the stability of the computational process, depending on the numerical method of solving the problem which is used, the smoothing procedure, and so on, but it is impossible in such an analysis to say anything definite about the sources of kinetic energy in the atmosphere, not to mention the cycle of energy conversion. At the same time, an actual increase (decrease) of the total kinetic energy takes place only due to conversion to other forms of energy, in particular, the valuable potential energy. The latter in turn is fulfilled primarily through the influx of heat. Consequently, total energy control, in addition to calculation of the components of the energy balance, must provide for an attempt to close the energy balance equation. The latter is possible only under the condition that the system correctly describes the cycle of conversion of the various forms of energy into one another. The more physical the model, the more accurately it will describe this mechanism.

As was shown in [6,11], for a closed air mass (the atmosphere /69
of the earth) the mechanism for the conversion of energy may be

described by the following balance equations: [1]

$$\left\{\frac{\partial K}{\partial t}\right\} = \{G\} - \{D\}; \qquad (1)$$

$$\{\varepsilon\} = \left\{\frac{\partial A}{\partial t}\right\} - \{G\}, \qquad (2)$$

where K is the kinetic energy
A is the useful potential energy
D and G are the dissipation and the generation of kinetic energy, respectively;
ε is all forms of influx of heat;
t is time.

The sign { } indicates averaging initially along the vertical, on the basis of mass, and then over the entire area.

The same equations are fulfilled in the case when a non-closed model is used, even if the limit of the region is reinforced, as is done in problems of precalculation for a limited territory through the setting of zero boundary conditions.

We will assume that the kinetic and useful potential energy of the system does not change significantly with time and from equations (1) and (2) we will have

$$\left\{\frac{\overline{\partial K}}{\partial t}\right\} = \left\{\frac{\overline{\partial A}}{\partial t}\right\} = 0,$$

whence

$$\{\bar{\varepsilon}\} = \{\overline{G}\} = \{\overline{D}\}. \qquad (3)$$

(Here the line indicates averaging with respect to time.)

It follows from (3), however, that the total influx of heat

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[1] Note that the difference in approaches developed in the works of Lorentz [11,18] and in our works [5, 6, 16] consists primarily in the methods of calculating the available or useful potential energy. The form of the balance equations that are used is the same.

into the atmosphere must be approximately equal to the generation or dissipation of kinetic energy. Obviously, under real conditions K and A will change with time, so that in analyzing equation (3) we can speak only of orders of magnitude. But this is important in itself. On the average, generation, like dissipation, of kinetic energy on the basis of various estimates comes to apprximately 5-10 watts per square meter. However, the influx of heat to the upper limit of the atmosphere is 350 watts $m^2$. Hence the atmosphere behaves like a "heat engine" with a very low efficiency of the order of 0.01 - 0.02. This is the basic difficulty in applying the energy balance equation in each time step in the integration of the dynamic equations. Similar attempts have led to the need to calculate small differences in large values, each of which is determined with considerable error. At the present time, the accuracy of calculation and measurement of various /70 forms of heat influx is so low that the errors are much greater than the value of G or D. In this connection, it has been stated that the closure of the energy balance equation is an insoluble problem.

Nevertheless, until it is solved, it will be impossible to use the laws of hydro- and thermodynamics to describe correctly the nature of the atmospheric processes and to require good quality on the part of precalculation of hydrometeorological fields.

Difficulties similar to those described above have already been encountered. Thus, for example, quite recently the construction of divergent models for precalculation requiring inclusion of data on actual wind, turned out to be unrealistic. Regardless of the relative accuracy in determining the wind speed, the calculation of the divergence could not be considered reliable: not only the sign, but the order as well, of the magnitude obtained created doubts. In this connection, in quasigeostrophic models divergence is excluded from vorticity equations by means of equations of continuity and of influx of heat. Nevertheless in recent years it has become possible to solve complete equations, and to use divergent models for precalculation on the basis of complete equations, generally without incorporating any data on the actual wind [10]. In this case the wind is calculated from equations of dynamics that are quite accurate, insuring agreement of the integrated equations. The quality of the precalculation on the basis of complete equations is much higher than when quasigeostrophic ones are employed.

Multilevel energy models of the atmosphere can possibly describe the fine mechanisms of conversion of various forms of energy including small scale turbulence in the boundary layers and the free atmosphere, as well as the mechanism for the formation of clouds. However, in many instances it is advisable to limit the problem to the small-parameter models of the atmosphere energetically equivalent to the real atmosphere.

As shown in [1, 4, 5, 6, 13, 17], the construction of a static model of the atmosphere which is energetically equivalent to the real one requires knowledge of only four parameters in all: $p_0$ which is the pressure at the surface characterizing the mass of a column of atmosphere of a uniform cross-section; $z_{av}$ which is the height of an average energy level characterizing the position of the center of gravity of a column of the atmosphere with a uniform cross-section; $T_{av}$ which is the temperature of an average energy level which is unambiguously linked to $z_{av}$ by the relationship $RT_{av} = gz_{av}$ (R is the gas constant, and g is the acceleration due to gravity), and it characterizes the average (with respect to mass) temperature of a column of atmosphere of uniform cross-section; $T_0$ is the temperature at the surface.

In [2, 15] the authors discussed some of the possible methods of constructing small parameter dynamic models of the atmosphere using the properties of the average energy level. The models were tested and revealed their workability only in instances linked to a sharp restructuring of the baric field [6, 12, 14].

Possible ways of using data from weather satellites in these models as raw data were discussed in [4, 8, 9]. /71

Let us examine the construction of a new dynamic small parameter model of the atmosphere using the properties of the average energy level and for an example let us attempt to illustrate one of the possibilities of achieving energetic control of the system. Its realization assumes solution of the resultant system of equations on the pattern of solution of complete equations.

The model in question will incorporate integral characteristics of the components of the wind speed which are analogous to the functions of the total fluxes for the ocean.

Let us write the equations for the dynamics of the atmosphere in a Cartesian isobaric system of coordinates:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + \omega^* \frac{\partial u}{\partial p} = -\frac{\partial H}{\partial x} + lv + \frac{\partial}{\partial p} kg^2\rho^2 \frac{\partial u}{\partial p} + \mu\cdot\nabla^2 u; \quad (4)$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+\omega^*\frac{\partial v}{\partial p}=-\frac{\partial H}{\partial y}-lu+$$

$$+\frac{\partial}{\partial p}kg^2\rho^2\frac{\partial v}{\partial p}+\mu\cdot\nabla^2 v; \tag{5}$$

$$\frac{\partial H}{\partial p}=-\frac{1}{\rho}; \tag{6}$$

$$p=\rho RT; \tag{7}$$

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial \omega^*}{\partial p}=0; \tag{8}$$

$$\frac{\partial}{\partial p}k_T g^2\rho^2\frac{\partial T}{\partial p}+\mu_T\cdot\nabla^2 T+\varepsilon_r+\varepsilon_m=jc_v\frac{dT}{dt}+p\frac{d}{dt}\left(\frac{1}{\rho}\right), \tag{9}$$

where u and v are the horizontal components of the wind speed on axes x and y;

$\omega^* = \frac{dp}{dt}$ is the vertical isobaric velocity;

p is the pressure;

$\rho$ is the density;

T is the temperature;

gz = H is the geopotential;

z is the linear altitude;

k and $k_T$ are the coefficients of vertical turbulent exchange for momentum and heat, respectively;

$\mu$ and $\mu_T$ are the coefficients of horizontal turbulent exchange for momentum and heat, respectively (usually $k = k_T$ and $\mu = \mu_T$ are used);

$\varepsilon_r$ is the influx of heat due to radiation;

$\varepsilon_m$ is the influx of heat due to phase transfers of moisture;

j is the mechanical equivalent of work;

$c_v$ is the specific thermal capacity with constant volume.

We will add to equation (1) the term $u\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial \omega^*}{\partial p}\right)=0$, /72 to equation (2) the term $v\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial \omega^*}{\partial p}\right)=0$ and integrate these equations with respect to p from the lower to the upper limits of the atmosphere. As the lower limit we will use the undisturbed surface of the open sea and as the pressure at the lower limit ($p_0$) we will use the reduced pressure to sea level.

Then

$$\int_0^{p_0}\left(\frac{\partial u}{\partial t}+\frac{\partial u^2}{\partial x}+\frac{\partial uv}{\partial y}+\frac{\partial u\omega^*}{\partial p}\right)dp=-\int_0^{p_0}\frac{\partial H}{\partial x}dp+$$
$$+l\int_0^{p_0}vdp+\int_0^{p_0}\mu\cdot\nabla^2 udp+\int_0^{p_0}\frac{\partial}{\partial p}kg^2\rho^2\frac{\partial u}{\partial p}dp; \qquad (10)$$

$$\int_0^{p_0}\left(\frac{\partial v}{\partial t}+\frac{\partial uv}{\partial x}+\frac{\partial v^2}{\partial y}+\frac{\partial v\omega^*}{\partial p}\right)dp=-\int_0^{p_0}\frac{\partial H}{\partial y}dp-l\int_0^{p_0}udp+$$
$$+\int_0^{p_0}\mu\cdot\nabla^2 vdp+\int_0^{p_0}\frac{\partial}{\partial p}kg^2\rho^2\cdot\frac{\partial v}{\partial p}dp. \qquad (11)$$

The equation of statics in integral form will be written as follows:

$$\int_0^{p_0}\frac{\partial H_p}{\partial p}dp=\int_0^{p_0}Hdp-\int_0^{p_0}RTdp. \qquad (12)$$

The derivative $H_p$ is equal to zero at the lower limit of the atmosphere with $z = 0$ ($p = p_0$) and at the upper limit of the atmosphere with $p \to 0$.

On the basis of (12) we will have

$$\int_0^{p_0}Hdp=R\int_0^{p_0}Tdp. \qquad (13)$$

Moving the average values of H (the central gravity of the column of atmosphere of uniform cross section) and $\overline{T}$ (the average temperature of the layer) out of the integrals we will have

$$\overline{H}p_0=R\overline{T}p_0,$$

or

$$\overline{H} = R\overline{T}. \tag{14}$$

However relationship (14) is satisfied for real values of H and T only at an average energy level, where the function $H_p$ reaches extreme value. As follows from (12), for the average energy level /73

$$\frac{\partial Hp}{\partial p} = 0 = H_{av} - RT_{av},$$

whence

$$H_{av} = RT_{av}. \tag{15}$$

The properties of the average energy level given by the author in 1957 are discussed in detail in [1, 4, 5, 6, 7, 13]. Here we should only mention that the conditions that follow from equations (13), (14), and (15), will be used by us to replace the average values of $\overline{H}$ and $\overline{T}$ by the values of $H_{av}$ and $T_{av}$ and for the mutual transition from $H_{av}$ to $T_{av}$ and from $T_{av}$ to $H_{av}$.

These conditions may be obtained from equation (7) as well, if we write it in integral form.

In fact, in accordance with the state equation

$$\int_0^{p_0} \frac{p}{\rho} dp = R \int_0^{p_0} T dp.$$

Substituting dp from the static equation, we will have

$$\int_0^{\infty} p dz = \frac{R}{g} \int_0^{p_0} T dp.$$

Integrating by parts, we will have

$$pz \Big|_0^{\infty} + \int_0^{p_0} z dp = \frac{R}{g} \int_0^{p_0} T dp. \tag{16}$$

In view of the fact that the function pz is equal to zero at the upper and lower limits of the atmosphere, and taking the average values $\overline{Z}$ and $\overline{T}$ out from beneath the integral signs, we will have condition (14).

Of course, it is also possible to get these same conditions from purely energetic relationships.

Integrals of the form

$$\int_0^{p_0} z dp = \int_0^{\infty} p dz = \frac{R}{g} \int_0^{p_0} T dp$$

are nothing more than the potential energy of a column of atmosphere of a uniform cross section. The internal energy of such a column will be determined by the expression

$$J = \frac{jc_v}{g} \int_0^{p_0} T dp.$$

According to the theory of Dines /74

$$\frac{\frac{jc_v}{g} \int_0^{p_0} T dp}{\frac{R}{g} \int_0^{p_0} T dp} = \frac{1}{\varkappa - 1},$$

whence

$$\frac{jc_v \overline{T} p_0}{\overline{z} p_0 g} = \frac{1}{\varkappa - 1},$$

or

$$R\overline{T} = g\overline{z}.$$

For the average energy level, the ratio of the internal energy of a unit mass to the potential energy will be

$$\frac{jc_v T_{av}}{g z_{av}} = \frac{1}{\varkappa - 1},$$

whence

$$RT_{av} = gz_{av}.$$

This condition is fulfilled only on one level, which makes it possible to assume that $z_{av} = \overline{z}$ and $T_{av} = \overline{T}$.

Let us write the equations of continuity and influx of heat in integral form, converting the latter by using the state equations

$$\int_0^{p_0} \left( \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial \omega^*}{\partial p} \right) dp = 0; \tag{17}$$

$$\int_0^{p_0} \frac{\partial}{\partial p} k_T g^2 \rho^2 \frac{\partial T}{\partial p} dp + \int_0^{p_0} \mu_T \cdot \nabla^2 T dp + \int_0^{p_0} (\varepsilon_x + \varepsilon_{\text{ф}}) dp =$$
$$= jc_p \int_0^{p_0} \frac{dT}{dt} dp + \int_0^{p_0} \frac{1}{\rho} \frac{d\rho}{dt} dp. \tag{18}$$

Let us introduce the integral components of the wind speed

$$U = \int_0^{p_0} u dp; \quad V = \int_0^{p_0} v dp. \tag{19}$$

These characteristics are analogous to the components of the function of total flux widely used in oceanology, although this is not always the same. Here, as an independent variable, we will use pressure, while in problems involving oceanic circulation it is usually depth that is used.

We can show that the integral characteristics of wind speed are determined sufficiently well by the characteristics of the average energy level. For this purpose let us write (4) without taking into account the term with the horizontal viscosity /75 in the form

$$\frac{1}{l}\left(\dot{u}+\frac{\partial H}{\partial x}+\frac{\partial \tau_x}{\partial p}\right)=v, \tag{20}$$

where $\dot{u}=\frac{du}{dt}$; $\tau_x = kg^2\rho^2\frac{\partial u}{\partial p}$ is the component force exerted by turbulent friction on axis x.

Integrating expression (20) with respect to p from p = 0 to $p = p_0$

$$\int_0^{p_0} vdp = V = \frac{1}{l}\left(\int_0^{p_0}\dot{u}dp+\int_0^{p_0}\frac{\partial H}{\partial x}\,dp+\tau_{x_0}\right). \tag{21}$$

However

$$\int_0^{p_0}\frac{\partial H}{\partial x}\,dp=\frac{\partial}{\partial x}\int_0^{p_0}Hdp=\frac{\partial \bar{H}p_0}{\partial x}=\frac{\partial H_c p_0}{\partial x}, \tag{22}$$

so that

$$V=\frac{1}{l}\frac{\partial H_c p_0}{\partial x}+\frac{\bar{\dot{u}}\cdot p_0}{l}+\frac{\tau_{x_0}}{l}. \tag{23}$$

Similarly, we will have

$$U=-\frac{1}{l}\cdot\frac{\partial H_c p_0}{\partial y}+\frac{\bar{\dot{v}}\cdot p_0}{l}+\frac{\tau_{y_0}}{l}, \tag{24}$$

where $\bar{\dot{u}}$ and $\bar{\dot{v}}$ are values for acceleration averaged with respect to the vertical and

$\tau_{x_0}$ and $\tau_{y_0}$ are the forces of turbulent friction.

The estimate shows that $\bar{\dot{u}}$ and $\bar{\tau}_{x_0}$, $\bar{\dot{v}}$ and $\bar{\tau}_{y_0}$ make a small contribution to the total wind speed. Hence U and V will be determined primarily by the components of the gradient of the function $H_{av}p_0$.

If in (19) we move the average value of u and v out of the integral signs we will have

$$U=\bar{u}p_0; \qquad V=\bar{v}p_0. \tag{25}$$

Hence, without great error,

$$\bar{u}=u_{av}; \qquad \bar{v}=v_{av},$$

where $u_{av}$ and $v_{av}$ are the component speeds at the average energy level. In a geostrophic wind /76

$$U=U_g=-\frac{1}{l}\cdot\frac{\partial H_{av}p_0}{\partial y};$$

$$V=V_g=\frac{1}{l}\cdot\frac{\partial H_{av}}{\partial x},$$

These expressions can be used as zero approximations for U and V.

Now let us carry out integration of the equations we have obtained, using the rule of integration of the function with the upper limit given.

As the boundary conditions at the upper and lower limits of the atmosphere, we will use the following.

At the upper limit of the atmosphere (p=0)

$$\omega^*=0; \quad kg^2\rho^2\frac{\partial u}{\partial p}=kg^2\rho^2\frac{\partial v}{\partial p}=k_T g^2\rho^2\frac{\partial T}{\partial p}=0;$$

$$\varepsilon_m=0; \quad \varepsilon_T=J_\infty^{\downarrow}-(B_\infty^{\uparrow}+J_\infty^{\uparrow}),$$

where $J_\infty^{\downarrow}$ — is the influx of shortwave radiation from above
$B_\infty^{\uparrow}$ — is the flux of long wave radiation from below
$J_\infty^{\uparrow}$ — is the flux of reflected short wave radiation upward.

At the lower limit of the atmosphere ($p = p_0$)

$$u = u_0; \quad v = v_0; \quad w = w_0 = 0;$$
$$\omega^* = \frac{\partial p_0}{\partial t} + u_0 \frac{\partial p_0}{\partial x} + v_0 \frac{\partial p_0}{\partial y} \cong \frac{\partial p_0}{\partial t};$$
$$kg\rho_0^2 \frac{\partial u}{\partial p}\Bigg|_{p=p_0} = -\rho_0 kg \frac{\partial u}{\partial z}\Bigg|_{z=0} = \tau_{x_0};$$
$$kg\rho_0^2 \frac{\partial v}{\partial p}\Bigg|_{p=p_0} = -\rho kg \frac{\partial u}{\partial z}\Bigg|_{z=0} = \tau_{y_0};$$
$$k_{\text{т}} g^2 \rho^2 \frac{\partial T}{\partial p}\Bigg|_{p=p_0} = -k_{\text{т}} g\rho_0 \frac{\partial T}{\partial z}\Bigg|_{z=0} = \varepsilon_{T_0};$$
$$T = T_0.$$

We can say with a sufficient degree of accuracy that $\partial p_0/\partial t = \rho_0 g\, \partial z_0/\partial t$ where t is any one of the variables x, y, and t; and $z_0$, the altitude of the isobaric surface $p_0$, is constant. The characteristics of turbulent exchange at the atmosphere-subjacent surface interface as well as the radiation balance will either be given or calculated by means of indirect data. It should also be noted that setting the boundary conditions in this form is only valid for the level of the open sea. Above dry land, taking orography into account leads to certain changes in these equations.

Having integrated (4) we will have /77

$$\int_0^{p_0} \left(\frac{\partial u}{\partial t} + \frac{\partial u^2}{\partial x} + \frac{\partial uv}{\partial y} + \frac{\partial u\omega^*}{\partial p}\right) dp = \frac{\partial}{\partial t}\int_0^{p_0} u\,dp - u_0 \frac{\partial p_0}{\partial t} +$$
$$+ \frac{\partial}{\partial x}\int_0^{p_0} u^2 dp - u_0 u_0 \frac{\partial p_0}{\partial x} + \frac{\partial}{\partial y}\int_0^{p_0} uv\,dp - u_0 v_0 \frac{\partial p_0}{\partial y} + u_0\omega_0^* =$$
$$= \frac{\partial U}{\partial t} + \frac{\partial}{\partial x}\int_0^{p_0} u^2 dp + \frac{\partial}{\partial y}\int_0^{p_0} uv\,dp;$$
$$\int_0^{p_0} \left(\frac{\partial v}{\partial t} + \frac{\partial uv}{\partial x} + \frac{\partial v^2}{\partial y} + \frac{\partial v\omega^*}{\partial p}\right) dp = \frac{\partial V}{\partial t} + \frac{\partial}{\partial x}\int_0^{p_0} uv\,dp + \frac{\partial}{\partial y}\int_0^{p_0} v^2 dp;$$
$$\int_0^{p_0} \frac{\partial H}{\partial x}\,dp = \frac{\partial}{\partial x}\int_0^{p_0} H\,dp - H_0 \frac{\partial p_0}{\partial x} = \frac{\partial H_{\text{av}} p_0}{\partial x};$$
$$\int_0^{p_0} \frac{\partial H}{\partial y}\,dp = \frac{\partial H_{\text{av}}}{\partial y};$$

$$\int_0^{p_0} \frac{\partial \tau_x}{\partial p} dp = \tau_{x0};$$

$$\int_0^{p_0} \frac{\partial \tau_y}{\partial p} dp = \tau_{y_0};$$

$$\int_0^{p_0} \mu \cdot \nabla^2 u dp = \mu \cdot \nabla^2 U;$$

$$\int_0^{p_0} \mu \cdot \nabla^2 v dp = \mu \cdot \nabla^2 V.$$

(In the last two integrals, there are additional terms that constitute combinations of $u_0$, $v_0$, $p_0$, and their derivatives. If we assume that in the boundary conditions $u_0 = v_0 = 0$, these terms will drop out.)

Taking these conversions into account, the equations of motion that have been averaged with respect to the vertical may be written as follows:

$$\frac{\partial U}{\partial t} = -\frac{\partial}{\partial x}\int_0^{p_0} u^2 dp - \frac{\partial}{\partial y}\int_0^{p_0} uv dp - \frac{\partial H_{av} p_0}{\partial x} + lV + \tau_{x_0} + \mu \cdot \nabla^2 U; \qquad (26)$$

$$\frac{\partial V}{\partial t} = -\frac{\partial}{\partial x}\int_0^{p_0} uv dp - \frac{\partial}{\partial y}\int_0^{p_0} v^2 dp - \frac{\partial H_{av} p_0}{\partial y} - lU + \tau_{y_0} + \mu \cdot \nabla^2 V. \qquad (27)$$

The equation of continuity (17) after integration gives us /78

$$\frac{\partial}{\partial x}\int_0^{p_0} u dp - u_0 \frac{\partial p_0}{\partial x} + \frac{\partial}{\partial y}\int_0^{p_0} v dp - v_0 \frac{\partial p_0}{\partial y} + \omega_0^* = 0,$$

or, taking into account the expression for $\omega_0^*$ and the boundary condition $w = 0$, with $z = 0$

$$\frac{\partial p_0}{\partial t} = -\left(\frac{\partial U}{\partial x} + \frac{\partial V}{\partial y}\right). \qquad (28)$$

Let us integrate further the equation of the first law of thermodynamics. We will represent all heat fluxes by ε, and rewrite equation (18) as follows:

$$\int_0^{p_0} \varepsilon dp = jc_v \int_0^{p_0} \frac{dT}{dt} dp + \int_0^{p_0} p \frac{d}{dt}\left(\frac{1}{\rho}\right) dp =$$

$$= jc_p \int_0^{p_0} \frac{dT}{dt} dp - \int_0^{p_0} \frac{\omega^*}{\rho} dp. \qquad (29)$$

The term $\int_0^{p_0} \frac{\omega^*}{\rho} dp$ determines the magnitude of generation of kinetic energy represented in equations (1) and (2) by G. However, in the integral form, the principal contribution to G is given by the term $R\int_0^{p_0} \frac{dT}{dt} dp$ with the residual term $\int_0^{p_0} p \frac{d}{dt}\left(\frac{1}{\rho}\right) dp$, characterizing the work of expansion, which is proportional to $\frac{1}{\rho} \cdot \frac{dp}{dt}$--the individual change in a column of atmosphere of a unit cross-section.

Taking into account the small size of this term, equation (9) may be written in the following form with considerable accuracy:

$$\int_0^{p_0} \varepsilon dp = jc_p \int_0^{p_0} \frac{dT}{dt} dp - R\int_0^{p_0} \frac{dT}{dt} dp = jc_v \int_0^{p_0} \frac{dT}{dt} dp.$$

However, the work of expansion can be taken into account more accurately.

Since

$$\int_0^{p_0} p \frac{d}{dt}\left(\frac{1}{\rho}\right) dp = -Rg \int_0^{\infty} T \frac{d\rho}{dt} dz,$$

following extraction of the average value of the temperature and the repeated application of the equation of statics, we will have /79

$$\int_0^{p_0} p \frac{d}{dt}\left(\frac{1}{\rho}\right) dp = -R\overline{T}\frac{\partial p_0}{\partial t}. \tag{30}$$

Then

$$\int_0^{p_0} \varepsilon dp = jc_v \int_0^{p_0} \frac{dT}{dt} dp - R\overline{T}\frac{\partial p_0}{\partial t}. \tag{31}$$

A simple estimate will show that the term $\frac{\partial p_0}{\partial t}$ is small in comparison with the influxes of heat and the change in internal energy, but it is important for the closure of the energy balance equation.

Let us add to the expression beneath the integral on the right-hand side of (31) the equation of continuity multiplied by T.

In this case

$$\begin{aligned} jc_v \int_0^{p_0} \frac{dT}{dt} dp - R\overline{T}\frac{\partial p_0}{\partial t} &= jc_v \left[\frac{\partial}{\partial t}\int_0^{p_0} T dp + \frac{\partial}{\partial x}\int_0^{p_0} uT dp + \right. \\ &\left. + \frac{\partial}{\partial y}\int_0^{p_0} vT dp - T_0\frac{\partial p_0}{\partial t} - u_0 T_0 \frac{\partial p_0}{\partial x} - v_0 T_0 \frac{\partial p_0}{\partial y} + \omega_0^* T_0\right] - RT\frac{\partial p_0}{\partial t} = \\ &= \frac{1}{\varkappa - 1}\left(\frac{\partial H_{av} p_0}{\partial t} + \frac{\partial H_{av} U}{\partial x} + \frac{\partial H_{av} V}{\partial y}\right) - RT\frac{\partial p_0}{\partial t}. \end{aligned} \tag{31a}$$

Here we make use of the fact that $\int_0^{p_0} T dp = T_{av} p_0$, $T_{av} = \frac{H_{av}}{R}$,

$U = \overline{u} p_0$, $V = \overline{v} p_0$, $\varkappa = \frac{c_p}{c_v}$.

The equation of the first law of thermodynamics, integrated with respect to p, now assumes the following form:

$$\frac{1}{\varkappa - 1}\left(\frac{\partial H_{av} p_0}{\partial t} + \frac{\partial H_{av} U}{\partial x} + \frac{\partial H_{av}}{\partial y}\right) - RT_c\frac{\partial p_0}{\partial t} = \int_0^{p_0} (\varepsilon_r + \varepsilon_m) dp +$$

$$+\varepsilon_{T_0}+\mu_{T_0}\left\{\nabla^2 T_{av}p_0-\left[T_0\nabla^2 p_0-2\left(\frac{\partial T_0}{\partial x}\cdot\frac{\partial p_0}{\partial x}+\frac{\partial T_0}{\partial y}\cdot\frac{\partial p_0}{\partial y}\right)-\right.\right.$$
$$\left.\left.-\left(\frac{\partial p_0}{\partial x}\cdot\frac{\partial^2 T_0}{\partial x^2}+\frac{\partial p_0}{\partial y}\cdot\frac{\partial^2 T_0}{\partial y^2}\right)\right]\right\}. \qquad (32)$$

Here $\varepsilon_{T_0}$ is the turbulent heat flux at the lower limit of the atmosphere. The brackets result from integration of the terms that determine the horizontal turbulent exchange.

Solving equation (32) for the fraction $\frac{\partial H_{av}}{\partial t}$, we will have /80

$$\frac{\partial H_{av}}{\partial t}=-\frac{1}{p_0}\left(\frac{\partial H_{av}U}{\partial x}+\frac{\partial H_{av}V}{\partial y}\right)-H_{av}\frac{1-\varkappa}{p_0}\cdot\frac{\partial p_0}{\partial t}+\varepsilon_{T_0}\frac{\varkappa-1}{p_0}+$$
$$+\frac{\varkappa-1}{p_0}\int_0^{p_0}(\varepsilon_r+\varepsilon_m)\,dp+\frac{\varkappa-1}{p_0}\mu_T\left[\frac{1}{R}\nabla^2(H_{av}p_0)-T_0\nabla^2 p_0-\right.$$
$$\left.-2\left(\frac{\partial T_0}{\partial x}\cdot\frac{\partial p_0}{\partial x}+\frac{\partial T_0}{\partial y}\cdot\frac{\partial p_0}{\partial y}\right)-\left(\frac{\partial p_0}{\partial x}\cdot\frac{\partial^2 T_0}{\partial x^2}+\frac{\partial p_0}{\partial y}\cdot\frac{\partial^2 T_0}{\partial y^2}\right)\right]. \qquad (33)$$

Equation (33) can be obtained from energetic relationships as well.

Let us use the letter J to designate the internal energy of a column of atmosphere with a unit cross section. Then the energy balance equation will be valid, and in accordance with it, for a column of atmosphere with unit cross-section, without taking into account the work of expansion, we will have

$$\frac{\partial J}{\partial t}+div\,Jc=\int_0^\infty \varepsilon\rho dz, \qquad (34)$$

with $div\,J_{\underline{c}}=div_h Jc$, where the index h designates the horizontal divergence and c is the average wind in a column of atmosphere of unit cross-section.

However, the internal energy of a column of atmosphere of a unit cross section is unambiguously determined by the expression [1, 5]

$$J = \frac{jc_v T_c p_0}{g} = \frac{1}{\varkappa - 1} H_{av} p_0. \tag{35}$$

Substituting equation (35) in (34) and reducing to g, after substituting ε from (18), integrating and solving the resultant equation with respect to $\frac{\partial H_{av}}{\partial t}$, we can easily obtain equation (32) and then (33). In the adiabatic approximation, equation (33) is simplified still further

$$\frac{\partial H_{av}}{\partial t} = -\frac{1}{p_0}\left(\frac{\partial H_{av}}{\partial x}U + \frac{\partial H_{av}}{\partial y}V\right) - mH_{av}\frac{\partial p_0}{\partial t}, \tag{36}$$

where $m = \frac{2-x}{p_0}$

Now let us examine the non-linear terms in equations (26) and (27). Let $u = \overline{u} + u'$, $v = \overline{v} + v'$ where $u'$ and $v'$ are the deviations from the average values of u and v with respect to the vertical. Then /81

$$\int_0^{p_0} u^2 dp = \overline{u}^2 \int_0^{p_0} \left(1 + \frac{\overline{u'^2}}{\overline{u}^2}\right) dp = \overline{u}^2 p_0 = \frac{U^2}{p_0};$$

$$\int_0^{p_0} v^2 dp = \overline{v}^2 \int_0^{p_0} \left(1 + \frac{\overline{v'^2}}{\overline{v}^2}\right) dp = \overline{v}^2 p_0 = \frac{V^2}{p_0};$$

$$\int_0^{p_0} uv\, dp = \overline{u}\,\overline{v} \int_0^{p_0} \left(1 + \frac{\overline{u'v'}}{\overline{u}\,\overline{v}}\right) dp = \frac{UV}{p_0}. \tag{37}$$

The accuracy of this approximation is determined by the degree to which the ratios $\frac{\overline{u'v'}}{\overline{u}\,\overline{v}}$, $\frac{\overline{u'^2}}{\overline{u}^2}$ и $\frac{\overline{v'^2}}{\overline{v}^2}$ are less than unity.

In this case, the system of prognostic equations may be finally written as follows:

$$\frac{\partial U}{\partial t} = -\frac{\partial}{\partial x}\left(\frac{U^2}{p_0}\right) - \frac{\partial}{\partial y}\left(\frac{UV}{p_0}\right) - \frac{\partial H_{av} p_0}{\partial x} + lV + \tau_{x_0} + \mu \cdot \nabla^2 U; \tag{38}$$

$$\frac{\partial V}{\partial t} = -\frac{\partial}{\partial x}\left(\frac{U \cdot V}{p_0}\right) - \frac{\partial}{\partial y}\left(\frac{V^2}{p_0}\right) - \frac{\partial H_{\mathrm{av}} p_0}{\partial y} - lU + \tau_{y_0} + \mu \cdot \nabla^2 V; \quad (39)$$

$$\frac{\partial p_0}{\partial t} = -\frac{\partial U}{\partial x} - \frac{\partial V}{\partial y}; \quad (40)$$

$$\frac{\partial H_{\mathrm{av}}}{\partial t} = -\frac{1}{p_0}\left(\frac{\partial H_{\mathrm{av}} U}{\partial x} + \frac{\partial H_{\mathrm{av}} V}{\partial y}\right) - \frac{H_{\mathrm{av}}}{p_0}(2-\varkappa)\frac{\partial p_0}{\partial t} + \frac{\varkappa - 1}{p_0}\int_0^{p_0}(\varepsilon_{r} +$$
$$+ \varepsilon_{\mathrm{m}})\, dp + \frac{\varkappa - 1}{p_0}\varepsilon_{r_0} + \frac{\varkappa - 1}{p_0}\mu_{\tau}\left[\frac{1}{R}\nabla^2 H_{\mathrm{av}} p_0 - T_0 \nabla^2 p_0 -\right.$$
$$\left. -2\left(\frac{\partial T_0}{\partial x} \cdot \frac{\partial p_0}{\partial x} + \frac{\partial T_0}{\partial y} \cdot \frac{\partial p_0}{\partial y}\right) - \left(\frac{\partial p_0}{\partial x} \cdot \frac{\partial^2 T_0}{\partial x^2} + \frac{\partial p_0}{\partial y} \cdot \frac{\partial^2 T_0}{\partial y^2}\right)\right]. \quad (41)$$

If we do not take into account these terms and view the problem in the adiabatic approximation, which is permissible, for example, in solving problems of short term weather forecasting, the system of equations (38-40) is simplified as follows:

$$\frac{\partial U}{\partial t} = -\frac{\partial}{\partial x}\left(\frac{U^2}{p_0}\right) - \frac{\partial}{\partial y}\left(\frac{UV}{p_0}\right) - \frac{\partial H_{\mathrm{av}} p_0}{\partial x} + lV; \quad (42)$$

$$\frac{\partial V}{\partial t} = -\frac{\partial}{\partial x}\left(\frac{UV}{p_0}\right) - \frac{\partial}{\partial y}\left(\frac{V^2}{p_0}\right) - \frac{\partial H_{\mathrm{av}} p_0}{\partial y} - lU; \quad (43)$$

$$\frac{\partial p_0}{\partial t} = -\frac{\partial U}{\partial x} - \frac{\partial V}{\partial y}; \quad (44)$$

$$\frac{\partial H_{av}}{\partial t} = -\frac{1}{p_0}\left(\frac{\partial H_{av}U}{\partial x} + \frac{\partial H_{av}V}{\partial y}\right) - mH_{av}\frac{\partial p_0}{\partial t}. \qquad (45)$$

Here we have omitted, in addition to the nonadiabatic heat fluxes, all of the viscosity terms. In addition, in equation (45) we can drop the last term which governs the change in the geopotential of the average level (average temperature) due to the adiabatic expansion (compression) of the column of atmosphere of unit cross section as its mass changes. This term, as we have already pointed out, is very small. /82

Hence, we have obtained a system of four equations (38-41) or (42-45) to find four unknown functions U, V, $p_0$ and $H_{av}$. The solution of this system may be accomplished by one of the known methods, as set forth in [3, 10].

However, some remarks are in order regarding the system of equations that is obtained. In developing the nonadiabatic model, in addition to the four unknown functions mentioned above, it is necessary to calculate or forecast the temperature at the surface $T_0$. In order to find it, we use the condition of isopycnicity of the average energy level [1].

The condition of constancy of the density $\rho_{av}$ = const makes it possible in accordance with equation (7) to find

$$p_{av} = \rho_{av} H_{av} \qquad (46)$$

As was shown in [4], there is an unambiguous relationship between the pressure $p_{av}$ and $p_0$:

$$\frac{p_{av}}{p_0} = \left(\frac{1}{1+\lambda_a}\right)^{\frac{1}{\lambda_a}}, \qquad (47)$$

where

$$\lambda_a = \frac{T_0}{T_{av}} - 1 = \frac{RT_0}{H_{av}} - 1,$$

whence

$$T_0 = T_{av}(1+\lambda_d),$$

or

$$T_0 = \frac{H_{av}(1+\lambda_d)}{R}. \tag{48}$$

Hence, at each stage of integration of the system of equations which was obtained it is necessary to calculate $p_{av}$ according to (46) and to use the given $p_{av}$ and $p_0$ with the aid of equation (47) to determine $l_g$, and then find $T_0$ with the aid of equation (48).

One can also use condition (47) to exclude $\rho_{av}$, taking into account the isopynicity of the average energy level. In this case, it is necessary to obtain the fifth prognostic equation to find either $T_0$ directly or $\lambda_d$. Thus, differentiating equation (47) with respect to time and taking into account that $\frac{1}{\rho_{av}} \cdot \frac{\partial p_{av}}{\partial t} = \frac{\partial H_{av}}{\partial t}$, and in accordance with the condition of $\frac{\partial \rho_{av}}{\partial t} = 0$, we will have

$$\frac{\partial H_{av}}{\partial t} = \frac{H_{av}}{p_0} \cdot \frac{\partial p_0}{\partial t} + \frac{H_{av}}{\lambda_d^2} \cdot \frac{\lambda_d - (1+\lambda_d)\ln(1+\lambda_d)}{1+\lambda_d} \cdot \frac{\partial \lambda_d}{\partial t}. \tag{49}$$

However on the basis of equation (48) /83

$$\frac{\partial T_0}{\partial t} = \frac{1+\lambda_d}{R} \cdot \frac{\partial H_{av}}{\partial t} + \frac{H_{av}}{R} \cdot \frac{\partial \lambda_d}{\partial t}. \tag{50}$$

Substituting $\frac{\partial \lambda_d}{\partial t}$ from formula (49) in formula (50), we will have

$$\frac{\partial T_0}{\partial t} = \frac{1+\lambda_d}{R} \left\{ \left[ 1 + \frac{\lambda_d^2}{\lambda_d - (1+\lambda_d)\ln(1+\lambda_d)} \right] \frac{\partial H_{av}}{\partial t} - \frac{\lambda_d^2}{\lambda_d - (1+\lambda_d)\ln(1+\lambda_d)} \cdot \frac{H_{av}}{p_0} \frac{\partial p_0}{\partial t} \right\}. \tag{51}$$

Taking into account that $1+\lambda_a = \frac{RT_0}{H_{av}}$ and excluding $\lambda_\pi$ from equation (5) we will finally obtain

$$\frac{\partial T_0}{\partial t} = \frac{T_0}{H_{av}}\left[1 + \frac{(RT_0 - H_{av})^2}{H_{av}\left(RT_0 - H_{av} - RT_0 \ln \frac{RT_0}{H_{av}}\right)}\right]\frac{\partial H_{av}}{\partial t} - T_0 \frac{(RT_0 - H_{av})^2}{H_{av}\left(RT_0 - H_{av} - RT_0 \ln \frac{RT_0}{H_{av}}\right)} \cdot \frac{1}{p_0} \cdot \frac{\partial p_0}{\partial t}. \tag{52}$$

Combining equation (52) with the system of equations (38-41), we will obtain five prognostic equations for finding five unknown functions, $p_0$, $T_0$, $H_{av}$, $(T_{av})$, U and V.

Now let us deal with the possibilities of energetic monitoring within the framework of this small parameter model.

Let us add equations (4) and (5) to the energy equation. To do this, we multiply equation (4) by u, equation (5) by v and combine them.

Designating the kinetic energy of a unit mass by $K = \frac{u^2 + v^2}{2}$ we will have

$$\frac{\partial K}{\partial t} + u\frac{\partial K}{\partial x} + v\frac{\partial K}{\partial y} + \omega^*\frac{\partial K}{\partial p} = -u\frac{\partial H}{\partial x} - v\frac{\partial H}{\partial y} + u\frac{\partial \tau_x}{\partial p} + v\frac{\partial \tau_y}{\partial p} + \mu\,(u\nabla^2 u + v\nabla^2 v). \tag{53}$$

To the left side of equation (53), we now add the term $K\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial \omega^*}{\partial p}\right) = 0$, and to the right side $H\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial \omega^*}{\partial p}\right) = 0$ and integrate the resulting equation with respect to p.

Then /84

$$\frac{\partial}{\partial t}\int_0^{p_0} K\,dp - K_0\frac{\partial p_0}{\partial t} + \frac{\partial}{\partial x}\int_0^{p_0} uK\,dp - K_0 u_0 \frac{\partial p_0}{\partial x} + \frac{\partial}{\partial y}\int_0^{p_0} vK\,dp - v_0 K_0 \frac{\partial p_0}{\partial y} + K_0\omega_0^* = -\frac{\partial}{\partial x}\int_0^{p_0} Hu\,dp - \frac{\partial}{\partial y}\int_0^{p_0} Hv\,dp + H_0\left(u_0\frac{\partial p_0}{\partial x} + v_0\frac{\partial p_0}{\partial y}\right) - \int_0^{p_0} H\frac{\partial \omega^*}{\partial p}\,dp + \int_0^{p_0}\left(u\frac{\partial \tau_x}{\partial p} + v\frac{\partial \tau_y}{\partial p}\right)dp + \mu\int_0^{p_0}(u\cdot\nabla^2 u + v\cdot\nabla^2 v)\,dp. \tag{54}$$

We will let $\int_0^{p_0} K dp = k^*$, noting that $\frac{1}{g}\int_0^{p_0} K dp$ is the kinetic energy of a column of atmosphere of a unit cross-section, whose mass is $\frac{p_0}{g}$. In accordance with the formula (37) $k^* = \frac{1}{2p_0}(U^2+V^2)$.

Then the equation of balance following subtracting of the average velocity values $\bar{u}$ and $\bar{v}$ on the left and right hand sides, will be written as follows:

$$\frac{\partial K^*}{\partial t} + \frac{\partial \bar{u} K^*}{\partial x} + \frac{\partial \bar{v} K^*}{\partial y} = -\frac{\partial}{\partial x}\left(\bar{u}\int_0^{p_0} H dp - \frac{\partial}{\partial y}\left(\bar{v}\int_0^{p_0} H dp\right) + \right.$$
$$+ H\cdot\omega^*\Big|_0^{p_0} + \int_0^{p_0} \omega^* \frac{\partial H}{\partial p} dp + D_B^* + D_h^* \tag{55}$$

Here $D^*_B = \int_0^{p_0}\left(u\frac{\partial \tau_x}{\partial p} + v\frac{\partial \tau_y}{\partial p}\right) dp$ is the dissipation of the kinetic energy of a column of atmosphere of unit cross-section due to vertical inhomogeneity of flow (this value includes dissipation caused by friction at the earth and dissipation caused by turbulence within the column of atmosphere [1], $D^*_h = \mu\int_0^{p_0}(u\cdot\nabla^2 u + v\cdot\nabla^2 v)dp$ is the dissipation caused by the horizontal inhomogeneity of the flow.

Usually this factor is not taken into account. However, in mathematical simulation of circulation of the atmosphere for long periods of time, it cannot be disregarded. Practically speaking, in many systems it is taken into account by introducing a frictional viscosity or smoothing. Making use of the fact that /85

$$\int_0^{p_0} H dp = H_{av} p_0;\quad \bar{u} p_0 = U;\quad \bar{v} p_0 = V;\quad H\omega^*\Big|_0^{p_0} = 0.$$

$$\int_0^{p_0} \omega^* \frac{\partial H}{\partial p} dp = -\int_0^{p_0} \frac{1}{\rho}\cdot\frac{dp}{dt} dp = -g\int_0^{\infty} \frac{dp}{dt} dz =$$
$$= -R\int_0^{p_0} \frac{dT}{dt} dp - R\bar{T}\int_0^{p_0} \frac{d\rho}{dt} dz = -R\int_0^{p_0}\left[\left(\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} + \right.\right.$$
$$\left.\left. + v\frac{\partial T}{\partial y} + \omega^*\frac{\partial T}{\partial p}\right) + T\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial \omega^*}{\partial p}\right)\right] dp - RT_{av}\omega_0^* =$$
$$-\frac{\partial}{\partial t}\int_0^{p_0} RT dp - \frac{\partial}{\partial x}\int_0^{p_0} RTu dp - \frac{\partial}{\partial y}\int_0^{p_0} RTv dp - RT_0\omega_0^* =$$
$$= -\frac{\partial (H_{av}p_0)}{\partial t} - \frac{\partial (\bar{u}H_{av}p_0)}{\partial x} - \frac{\partial (\bar{v}H_{av}p_0)}{\partial y} - H_{av}\omega_0^*, \tag{56}$$

we then have

$$\frac{\partial K^*}{\partial t}+\frac{\partial \bar{u}K^*}{\partial x}+\frac{\partial \bar{v}K^*}{\partial y}=-\left[\left(\frac{\partial H_{av}U}{\partial x}+\frac{\partial (H_{av}V)}{\partial y}+\frac{\partial (H_{av}p_0)}{\partial t}\right)+\right.$$

$$\left.+\left(\frac{\partial UH_{av}}{\partial x}+\frac{\partial H_{av}V}{\partial y}+H_{av}\omega_0^*\right)\right]+D_{\text{в}}^*+D_{\text{H}}^*. \qquad (57)$$

The terms that are in brackets characterize the generation of kinetic energy which we shall designate by G. The first bracket shows generation due to the work of the forces of horizontal baric gradient. The second bracket comes into being because of the tterm, $\int\limits_{0}^{p_0}\omega^*\frac{\partial H}{\partial p}dp$ ; as we see, the work of the forces of horizontal baric gradient also comes in here.

If we integrate equation (57) with respect to area and take into account that

$$\int\limits_{(S)} div_h c\varphi^* dS=\int\limits_{(L)}\varphi^* c_n dl,$$

where $\phi^*$ is a certain substance (in this case $K^*$ or $H_{av}$);
$c_n$ is the normal component of the integral velocity to the contour L, enclosing a given area S;
dS and dl are elements of area and contour respectively, so that on the basis of equation (57) we will have

$$\left\{\frac{\partial K^*}{\partial t}\right\}=-\int\limits_{(L)}\frac{K^*}{p_0}c_n dl-\left\{\frac{\partial H_{av}p_0}{\partial t}\right\}-\int\limits_{(L)}2H_{av}c_n dl-(H_{av}\omega_0^*)+$$

$$+(D_{\text{в}}^*)+\{D_{\text{H}}^*\}. \qquad (58)$$

If the area is closed or boundary conditions are imposed on a non-closed area, in accordance with which the energy (mass) flux through the boundary of the contour cannot take place, on the basis of (58) we will have /86

$$\left\{\frac{\partial K^*}{\partial t}\right\}=-\left\{\frac{\partial H_{av}p_0}{\partial t}\right\}+\{D_{\text{в}}^*\}+\{D_{\text{H}}^*\}. \qquad (59)$$

This means that the change in kinetic energy must be determined by the magnitude of the dissipation and the change in the potential energy.

However, in accordance with equation (32), following its integration with respect to the area

$$\left\{\frac{\partial H_{av} p_0}{\partial t}\right\} = -\int_{(L)} H_{av} c_n dl - \{H_{av}\omega_0^*\} + \frac{1}{\varkappa - 1}\{\varepsilon^*\}, \tag{60}$$

where $\varepsilon^*$ represents all forms of heat flux $\omega_0^* = \frac{\partial p_0}{\partial t}$.

For a closed area or for unclosed area in the case of absence of energy (mass) flux through the boundary of the region, we will have

$$\left\{\frac{\partial H_{av} p_0}{\partial t}\right\} = \frac{1}{\varkappa - 1}\{\varepsilon^*\}. \tag{61}$$

Hence, the change in the potential energy can occur only due to the influx of heat.

Analyzing the above, we can draw the following conclusions.

If we have a closed area and deal with the problem in the adiabatic approximation, i.e., without influx of heat, the kinetic energy of the system can change only as a result of dissipation of $D^*_B$ and $D^*_h$. However, the latter always leads to a decrease in the kinetic energy. Consequently, if the adiabatic model for the closed area produces an increase in the kinetic energy, it is not an advantage but rather a shortcoming, since the growth of the kinetic energy can occur only at the expense of a change in the potential energy of the system $\frac{\partial H p_0}{\partial t}$, and the latter can change only by virtue of an influx of heat. Consequently, in the course of integration of the equations of the dynamics of the atmosphere, the balance equations of energy (59) and (61) and in a more general statement of the problem (58) and (60) must be fulfilled within the framework of those additional limitations which are imposed on a particular model.

In solving the nonadiabatic problem, consideration of the heat fluxes must result in some kind of a change in the potential energy, i.e.: $\frac{\partial H_{av} p_0}{\partial t} \neq 0$.

In accordance with the equation for the balance of kinetic energy for a closed area, real changes in kinetic energy cannot exceed the difference between the changes in the potential energy of the system and the magnitude of dissipation. If this is observed, then merely because of the computational procedure (instability of /87 computation, considerable smoothing), or by virtue of the fact that the original equations did not take into account some additional forces (a lack of constancy in the force of attraction, nutation of the poles, tidal phenomena, and so on). In any case, within the framework of the adopted limitations the balance equations of energy must be closed. If these equations are closed during integration within the framework of the adopted assumptions, but the results do not agree with the actual data, the reason evidently lies in the physical statement of the problem.

The potential energy itself is included in the balance equations which are obtained. From this it is easy to shift to the useful potential energy which is determined by the parameters that go to make up the prognostic system of equations, in particular, through the characteristics of the average energy level [5, 6].

The mechanism through which the heat energy changes into potential energy in the final analysis, as we can see from equation (55), is determined by the work of the forces of baric gradient and to a large extent by the term $\omega^* \frac{\partial H}{\partial p}$. The summary action of this effect in the integral form in the model in question can be taken into account by the parameters of the average energy level. In multilevel baroclinic models the accuracy of closure of the balance equations for energy will depend to a large extent on the accuracy of computation of the vertical velocities.

In conclusion it should be pointed out that in the present paper the goal has been to illustrate possible ways of using the energy control in the example of a small parameter model of the atmosphere by an energetically equivalent real atmosphere. The results of the numerical experiments are not considered here.

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# ESTIMATE OF HEAT FLUXES ON THE SUBJACENT SURFACE (ACCORDING TO DATA FROM SYNOPTIC ANALYSIS) /89

A. P. Nagurnyy

The article discusses several methods of estimating heat fluxes from nonadiabatic sources, distributed over the subjacent surface. The calculations were performed for the entire territory of the northern hemisphere on the basis of data for a concrete meteorological period of measurement (0300, 3 February, 1958). Data from aerological sounding at the $AT_{500}$* and $AT_{400}$ level and the temperature of the subjacent surface were used.

Such calculations involve considerable difficulty inasmuch as there is no complete theory of heat transfer in the lower layer of the atmosphere. The problem is further complicated by the fact that the need for numerical simulation of the general atmospheric circulation in the problem of interaction between the hydrosphere and the atmosphere requires that the influence of nonadiabatic effects be considered exclusively through the characteristics of the meteorological elements which are measured at standard levels in the free atmosphere and on the ground.

These requirements can be satisfied only at the cost of a significant simplification of the mechanism of turbulent exchange in the lower layer of the atmosphere, and, in problems of planetary scale, by an a priori statement of the average parameters of the boundary layer, determined empirically.

One such mechanism may be studied under the conditions of a polytropic model of the atmosphere, which may be viewed as a first approximation to the real atmosphere.

The author of [5] suggests a three-layer polytropic model of the atmosphere and discusses the principle of construction of a model of the atmosphere using as a basis the equality of the potential and intrinsic energy of a vertical column of simulated and real atmosphere. In accordance with this principle, any model of the atmosphere will have a vertical stratification of temperature and a thickness such that the average mass temperature $T_m$ and the pressure near the ground $p_0$ will be equal to values observed in the real atmosphere.

In this case, the potential and intrinsic energy of the /90

*height pattern

vertical column of simulated and real atmosphere will be the same, since:

$$E_i = \frac{c_v}{A}\int_0^{p_0} T dp = \frac{c_v}{A} T_m p_0;$$

$$E_d = \frac{1}{g}\int_0^{p_0} \Phi dp = \frac{1}{g}\Phi_m p_0 = \frac{R}{g} T_m p_0,$$

where $E_i$, $E_d$ represent the intrinsic and potential energies of the vertical column respectively

g is the acceleration due to the force of gravity;

$\Phi$ is the geopotential and

$c_v$, A, R are thermodynamic constants.

$$T_m = \frac{1}{p_0}\int_0^{p_0} T dp; \quad \Phi_m = \frac{1}{p_0}\int_0^{p_0} \Phi dp.$$

In the latter equation, the Dines relation is taken into account, so that $RT_m = \Phi_m$.

In a three-layer polytropic model the polytropic analog of the vertical profile of the temperature in the planetary boundary layer may be written as follows:

$$-\frac{\partial T}{\partial z} = \gamma' = \frac{g\gamma'}{R} = c_1 - \frac{c_2 T_m + c_3}{T_0}, \tag{1}$$

where

$$c_1 = \left(\frac{2\ln\frac{p_0}{p_h}}{\ln^2\frac{p_h}{p_0}} - 1\right)\frac{g}{R};$$

$$c_2 = \frac{2\left(1 - \frac{p_h}{p_0}\right)}{\ln^2\frac{p_h}{p_0}} \cdot \frac{g}{R};$$

$$c_3 = \frac{2\gamma h p_h g}{R_{p_0}\ln^2\frac{p_h}{p_0}\left(\frac{\gamma R}{g} + 1\right)}.$$

The value of $T_m$ may be obtained on the basis of the interpolation formula [6]:

$$T_m = \frac{1}{R} \cdot \frac{\Phi_{500}(RT_{500} - RT_{400}) + RT_{500}(\Phi_{400} - \Phi_{500})}{(\Phi_{400} - \Phi_{500}) + R(T_{500} - T_{400})}, \tag{2}$$

Where $T_{500}$, $\Phi_{500}$, $T_{400}$, $\Phi_{400}$ represent the temperature and the geopotential $AT_{500}$ and $AT_{400}$;

$T_0$ is the temperature at the ground;

$p_h$ and $T_h$ are the pressure and temperature at the upper limit of the boundary layer; /91

$$\eta = \gamma \frac{R}{g}, \quad \gamma = 0.67°/100 \text{ м}, \quad T_h = T_m(1+\eta) - \gamma h$$

Where h is the altitude of the boundary layer.

The value of $\gamma'$ is highly dependent upon the change in temperature at the ground $T_0$. For real measurements of $T_0$ the value of $\gamma'$ can reach $\pm 5°/100$ meters.

The polytropic temperature gradient in the boundary layer may be viewed only as a first approximation to a real temperature profile, but in this gradient the energy contribution of the simulated boundary to the general balance of the potential and intrinsic energy of the entire column of the atmosphere is the same as that of a real boundary layer at a given moment in time.

Let us write the balance equation of the influx of heat on the subjacent surface:

$$Q_T + Q_q + Q_T^* = Q_S + Q_{(A-B)}, \tag{3}$$

where $Q^*_T$ is the heat flux in the soil,

$Q_T$ is the heat flux due to turbulent transfer in the boundary layer;

$Q_q$ is the heat flux due to phase conversions of water vapor and

$Q_S$ is the influx of short-wave radiation;

$Q_{A-B}$ is the longwave radiation balance (A is the upward flux and B is the downward flux).

Under the conditions of a polytropic model of the boundary layer, the turbulent heat flux, with consideration of equation (1), is written as follows:

$$Q_T = \lambda\left(\frac{\partial T}{\partial z} + \gamma_a\right) = \lambda\left[c_1 - \frac{c_2 T_m + c_3}{T_0} + \gamma_a\right],$$

where λ is the coefficient of turbulent thermoconductivity.

The heat flux due to phase conversions of water vapor by means of the familiar expression for specific humidity

$$q = \frac{3.81}{p_0} f' e^{a(T-273)}$$

is changed to the form

$$Q_q = \lambda \frac{L}{c_p}\frac{\partial q}{\partial z} = \lambda \frac{L}{c_p}\bar{f} a e^{a(T_0-273)}\left(c_1 - \frac{c_2 T_m + c_3}{T_0}\right), \tag{5}$$

where f' is the relative humidity

$a = 0.08 \frac{1}{\text{degree}}$;

L = specific heat, expended in vapor formation;

$c_p$ is the specific thermal capacity;

$\bar{f}$ is average relative humidity.

The heat flux in the soil $Q^*_t$, as indicated by numerous calculations, is small, and is disregarded as a rule. However, in the case of the surface of the ocean, this flux is rather high. However, the thermal inertia of the ocean is so great that the temperature of the upper layer of the ocean cannot rapidly follow the changes in temperature in the lower layer of the atmosphere, so that at any moment in time the surface temperature will always determine the value of the heat flux from the ocean to the lower limit of the atmosphere. The only exception is the case of an aquatorium covered with ice, the Arctic Basin. Heat transfer from the ocean through the ice into the atmosphere has been studied in detail in [3] by D. L. Laykhtman and in [1] Yu. P. Doronin. /92

D. L. Laykhtman proposed the following formula for determining the heat flux through the ice:

$$Q_T^* = \bar{\lambda}^* \frac{\vartheta_0 - T_0}{h_i + h_s}, \tag{6}$$

where

$$\bar{\lambda}^* = \frac{h_i + h_s}{\frac{h_i}{\lambda_i^*} + \frac{h_s}{\lambda_s^*}}, \quad \vartheta_0 = -1.8° \mathrm{C},$$

$h_i$ is the thickness of the ice cover;

$h_s$ is the thickness of the snow layer on the ice;

$\lambda_i^*$ is the coefficient of thermal conductivity of the ice;

$\lambda_s^*$ is the coefficient of thermal conductivity of the snow,

Equation (6) is best satisfied in winter, when the temperature gradient in the layer of ice and snow is close to a linear profile. On the right-hand side of equation (3) we can write the radiation balance on the surface of the earth. Then the shortwave radiation $Q_S$ will depend on the latitude, time of year, integral transparency of the atmosphere and the cloud cover. These factors are taken into account essentially in a semiempirical form [2].

Long wave fluxes directed downward (A) and upward (B) may be expressed in the first approximation as follows:

$$Q_{(A-B)} = A - B; \quad B\Big|_{z=0} \cong f_s \sigma T_0^4; \quad A\Big|_{z=0} \cong f_a \sigma T_m^4; \tag{7}$$

All terms of the balance equation are determined by $T_0$, $T_m$ and various physical constants. This makes it possible to determine $\lambda$ from (3). Substituting all of the terms on the right and left sides of the balance equation, we will have:

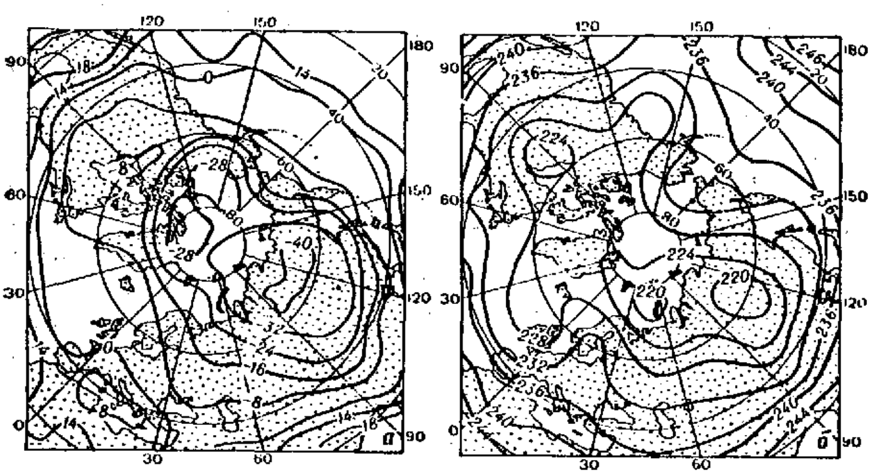
$$\lambda = kc_p\rho = \frac{Q_S + Q_{(A-B)} - \bar{\lambda}^* \frac{\vartheta_0 - T_0}{h_i + h_s}}{\left(c_1 - \frac{c_2 T_m + c_3}{T_0} + \gamma a\right)\left(1 + \frac{L}{c_p} \cdot \frac{3.81}{p_0} \bar{f} a e^{a(T_0 - 273)}\right)},$$

where $k$ is a coefficient of turbulent exchange and $\rho$ is the density.

The latter equation makes it possible to close physically the heat balance equation on the surface of the earth within the framework of the boundary layer model which has been adopted and to compensate somewhat for the roughness of the model itself in calculating individual components of thermal balance. /93

Within the limits of real measurements of $T_0$ and $T_m$ with h = 0.5 kilometer, the value of k will vary from 5 to 50 $m^2$ per second, which is in complete agreement with the order of magnitude of the coefficient of turbulence determined according to experimental data [4].

Figure 1 a and b show the distribution of $T_0$ and $T_m$ over the entire northern hemisphere at 0300 hour on 3 February 1958. The temperature $T_m$ was calculated according to formula (2). The altitude of the thermal boundary layer was assumed to be 900 mb.



a b

Figure 1. Distribution of the temperature at the ground $T_0$(a) and the average temperature $T_m$(b) at 0300 hour on 3 February 1958.

In this synoptic situation, the minimal values for the average temperature reached 220°K, and the maximum values were observed around the equatorial belt reaching 250°K. The latitudinal temperature contrast on the whole is 30%. At the same time, the maximum latitudinal contrast between the temperature on the ground (see Figure 1B) was 72°, and the isolines of the field $T_0$ and $T_m$ do not coincide in their configuration, while the centers of minimal and maximal values of $T_m$ and $T_0$ were displaced relative to one another indicating that according to formulas 4-7 there is a different degree of intensity of heat exchange in different geographical regions.

Figure 2 shows the distribution of heat fluxes calculated

according to formulas 4-7. The maximum absolute value is that of the heat flux caused by long wave radiation from the earth's surface--$Q_{A-B}$. In all geographical regions, this flux is directed into the atmosphere and in a given meteorological situation changes within limits of $4 \cdot 10^{-2}$ calories per cm$^2$·sec at low latitudes and $0.5\ 10^{-2}$ calories cm$^2$·sec in the polar regions. The rapid decrease in the flux $Q_{A-B}$ from the equator to the high latitudes means that in the polar regions $Q_{A-B}$ becomes comparable in magnitude to the heat flux from the ocean through the ice $Q^*_T = 0.3 \cdot 10^{-2}$ calories per cm$^2$·sec. It is characteristic that if $Q_{A-B}$ is always the /94
outgoing portion in the heat balance on the subjacent surface, the fluxes $Q^*_T$ and $Q_T$ at high latitudes are the incoming part of the balance which compensates for heat loss through radiation in those regions where the arrival of shortwave radiation is absent or very small.

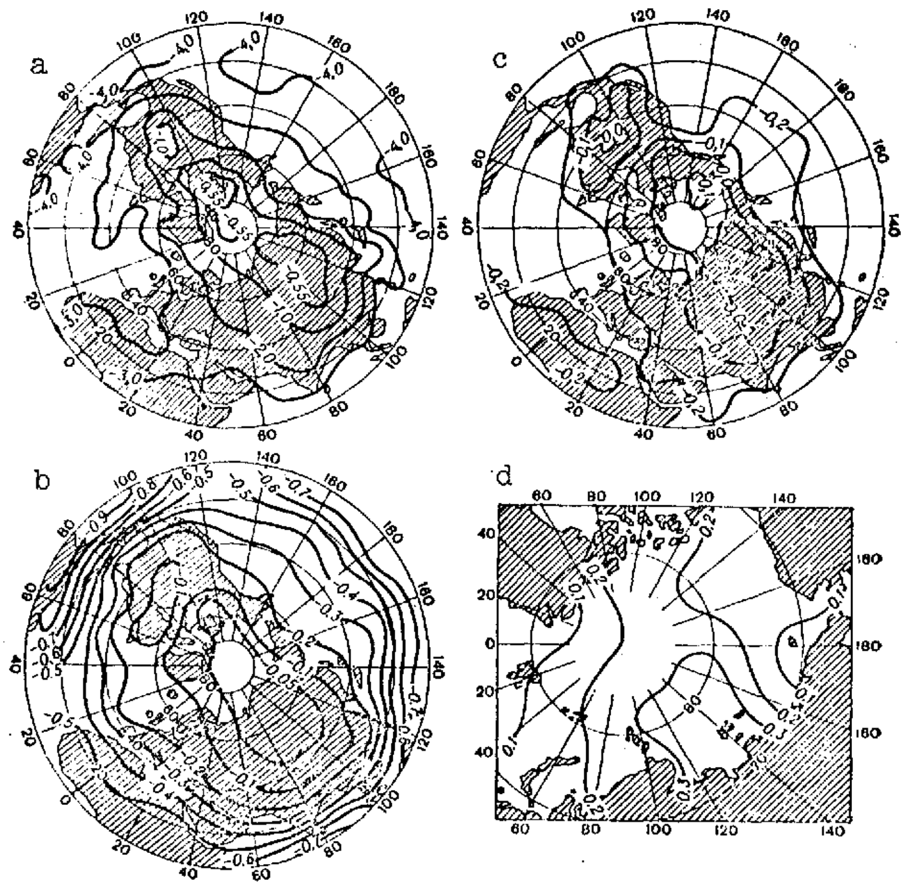



Figure 2. Distribution of flux $Q^*_{A-B}$ (a) $Q_q$ (b) $Q_T$ (c) $Q^*_T$ (d) at 0300 hour on 3 February 1958 ($10^{-2}$calories per cm$^2$·sec).

It must also be pointed out that there are some characteristics of the distribution of heat flux caused by phase conversions of water vapor in the boundary layer. The flux $Q_q$ is almost ten times greater than the flux $Q_T$ in a narrow equatorial zone, but as the latitude increases its magnitude rapidly decreases and at high latitudes becomes about half the value of $Q_T$. The heat flux due to turbulent transfer (see Figure 2c) has values from $-0.2 \cdot 10^{-2}$ to $0.1 \cdot 10^{-2}$ calories per $cm^2 \cdot sec$. At equatorial and middle latitudes, this flux is directed from the subjacent surface into the atmosphere. In the polar regions and in the central portion of the Asiatic continent it moves in the opposite direction. Here the atmosphere gives up heat to the surface of the earth. /95

The distribution of heat flux from the ocean through the ice to the lower limit of the atmosphere is shown in Figure 2d. A comparison of the magnitude of this flux with other components of the thermal balance will show that the flow of heat from the ocean in winter makes the same contribution as the flux $Q_{A-B}$ or the flux $Q_T$. The maximum value of $Q^*_T = 0.3 \cdot 10^{-2}$ calories per $cm^2 \cdot sec$ is completely comparable with the value of the flux $Q_{A-B}$ in the given region and is twice as large as the value $Q_T$.

There are certain general features that can be detected in the geographical distribution of all fluxes. The zonality in the distribution of heatfluxes from the equator to the pole as well as the considerable influence of the continents are quite evident. It is possible to distinguish four characteristic regions of localization of extremal heat flux values caused by the influence of the subjacent surface: a zone of the equatorial belt and the warm sectors of the Atlantic and Pacific Oceans, the zone of the Asiatic continent, the zone of the North American continent, the zone of the Arctic Basin. On the whole, there is a tendency toward predominance of the fluxes $Q_{A-B}$ and $Q_q$ at low latitudes with a gradual balancing of the magnitude of all the fluxes at high latitudes. It is characteristic that the role of the fluxes $Q_{A-B}$, $Q_T$ and $Q^*_T$ in the polar regions is the same.

The distribution of heat fluxes on the subjacent surface, shown in Figure 2, agrees completely with known concepts regarding the nature of the distribution of these fluxes, which indicates the qualitative effectiveness of the adopted model of the boundary layer. This provides a basis for using the model in a numerical system of simulation of the general circulation of the atmosphere.

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# A SMALL PARAMETER MODEL OF CIRCULATION IN AN HOMOGEONEOUS BAROCLINIC OCEAN /96

Ye. P. Borisenkov

In solving problems of precalculation of atmospheric circulation, small parameter models of the atmosphere have been widely employed; they make it possible to obtain nonlinear diagnostic and prognostic equations which are averaged with respect to the vertical [4]. A classical example of such equations is the diagnostic equation of balance and the prognostic barotropic equation of vorticity. The first makes it possible to make the transition from a pressure field to a stream function and velocity field or from a velocity field to a pressure field, while the second makes it possible to express the stream function for some average level, i.e., to solve the nonstationary problem. In studying the dynamics of the ocean, equally broad publication has been given to methods based on the solution of the problem of determining the function of the total fluxes. The most complete survey of studies using this method will be found in [6]. There is a certain analogy between these methods, developed independently of one another in dynamic meteorology and dynamic oceanology, which makes it possible to use them in constructing small parameter nonlinear models of circulation of the ocean both for stationary and nonstationary cases. A similar interpenetration of methods of dynamic meteorology and dynamic oceanology is becoming increasingly frequent in recent times and is unquestionably leading to further progress in the solution of the joint problem of circulation of the atmosphere and the ocean.

Taking into account the limited number of observations made in the ocean, especially in its depth, the conduct of numerical experiments with multilevel hydrodynamic models for the ocean will obviously be a difficult task and small parameter models of a baroclinic ocean must accordingly find a broad sphere of application for the solution of both stationary and nonstationary problems of oceanic circulation.

The present paper has as its purpose the discussion of one of the possible approaches to the solution of the problem of oceanic circulation, using the above mentioned common nature of the principles of construction of small parameter models and certain energetic principles developed in connection with atmospheric processes [1, 2] and which have found a completely justifiable analogy in the study of processes in a baroclinic ocean [3]. /97

Let us write the original system of equations in a rectangular system of coordinates: /97

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}-lv=-\frac{1}{\rho}\cdot\frac{\partial p}{\partial x}+$$
$$+\frac{1}{\rho}\cdot\frac{\partial}{\partial z}k\rho\frac{\partial u}{\partial z}+A\nabla^2 u; \tag{1}$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}+lu=-\frac{1}{\rho}\cdot\frac{\partial p}{\partial y}+$$
$$+\frac{1}{\rho}\cdot\frac{\partial}{\partial z}k\rho\frac{\partial v}{\partial z}+A\nabla^2 v; \tag{2}$$

$$\frac{\partial p}{\partial z}=+\rho g; \tag{3}$$

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0; \tag{4}$$

$$\rho=\rho(p, T, S); \tag{5}$$

$$\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}+w\frac{\partial T}{\partial z}=\frac{\partial}{\partial z}k_1\frac{\partial T}{\partial z}+A_1\nabla^2 T+\varepsilon; \tag{6}$$

$$\frac{\partial S}{\partial t}+u\frac{\partial S}{\partial x}+v\frac{\partial s}{\partial y}+w\frac{\partial s}{\partial z}=\frac{\partial}{\partial z}k_2\frac{\partial s}{\partial z}+A_2\nabla^2 S+\Delta S, \tag{7}$$

where u, v and w are the components of the rate of flow on axes x, y, and z;

p is the pressure;

$\rho$ is the density;

T is the temperature;

S is the salinity;

g is the acceleration due to the force of gravity;

$l = 2\omega\sin\phi$ is the Coriolis parameter;

k, $k_1$ and $k_2$ are the coefficients of turbulence for a vertical exchange of momentum, heat, and salts, respectively;

A, $A_1$, $A_2$ are the corresponding coefficients of turbulence for horizontal exchange;

$\Delta S$ is the change in salinity due to desalination of the active layer through the melting of ice, precipitation, influx of fresh water, and so on;

$\varepsilon$ is the influx of heat due to absorption of solar radiation, phase transitions of moisture on the surface, heat losses due to radiation, etc. (The indicated influx of heat is encountered primarily in the active layer of the ocean.)

The vertical coordinate is directed from the surface downward, and the origin of the coordinates is located on the calm surface of the ocean. /98

If the heat flux $\varepsilon$ and $\Delta S$ is not taken into account in equations (6) and (7) and we consider that $k_1 = k_2$, $a_1 = a_2$, and also use the equation of the state of the sea water in the linear approximation, in accordance with equation 4 they will boil down to a single equation for density:

$$\frac{\partial\rho}{\partial t}+u\frac{\partial\rho}{\partial x}+v\frac{\partial\rho}{\partial y}+w\frac{\partial\rho}{\partial z}=\frac{\partial}{\partial z}k_1\frac{\partial\rho}{\partial z}+A_1\nabla^2\rho. \tag{8}$$

Let us now solve the system of equations (1)-(5) disregarding the changes in density with time.

Let

$$\rho=\rho_m+\rho', \tag{9}$$

where

$\rho_m$ = the density at the bottom

$\rho'$ = deviation in density from $\rho_m$.

Usually $\rho_m$ will have a maximum value which will be reached at some distance from the bottom.

In this case the equation of statics, integrated from $z = \varepsilon$ to $z$ where $\varepsilon$ is the altitude of the level, i.e., the deviation of the surface of the sea from its calm position $z = 0$, will assume the following form:

$$\int_{p|_{z=\xi}}^{p|_z} dp = \int_{\xi}^{z} \rho_m g dz + \int_{\xi}^{z} \rho' g dz.$$

Following integration and the change in the limits of integration, in the last term on the right hand side for some level z we will have

$$p = p_a + \rho_m g (z - \xi) - g \int_{z}^{\xi} \rho' dz, \tag{10}$$

or

$$p = p_a + \rho_m g (z - \xi) + q, \tag{11}$$

where

$$q = -g \int_{z}^{\xi} \rho' dz;$$

$p_a$ is the atmospheric pressure. For the entire column of water of uniform cross section

$$p_H = p_a + \rho_m g (H - \xi) - g \int_H^{\xi} \rho' dz, \qquad (12)$$

where H is the depth of the sea. This representation of density, /99
as was shown in [3] makes it possible in pure form to exclude the baroclinicity of the ocean and give it a comparatively simple energetic interpretation which has an analogy in the atmosphere (usually the average density value is used instead of $\rho_m$).

With $z \to H$, $q = q_z \to q_H$ and reaches its maximum value in absolute magnitude.

On the basis of formula (11) we will have

$$\frac{\partial p}{\partial x} = \frac{\partial p_a}{\partial x} + \frac{\partial q}{\partial x} + \rho_m g \frac{\partial (z - \xi)}{\partial x} + g (z - \xi) \frac{\partial \rho_m}{\partial x}; \qquad (13)$$

$$\frac{\partial p}{\partial y} = \frac{\partial p_a}{\partial y} + \frac{\partial q}{\partial y} + \rho_m g \frac{\partial (z - \xi)}{\partial y} + g (z - \xi) \frac{\partial \rho_m}{\partial y}. \qquad (14)$$

The equations of motion involving consideration of equations (13) and (14) will assume the following form:

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} - lv = -\frac{1}{\rho} \cdot \frac{\partial p_a}{\partial x} - \frac{\rho_m g}{\rho} \cdot \frac{\partial (z - \xi)}{\partial x} -$$

$$- g \frac{(z - \xi)}{\rho} \frac{\partial \rho_m}{\partial x} - \frac{1}{\rho} \cdot \frac{\partial q}{\partial x} + \frac{1}{\rho} \cdot \frac{\partial}{\partial z} k\rho \frac{\partial u}{\partial z} + A \nabla^2 u; \qquad (15)$$

$$\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} + lu = -\frac{1}{\rho} \cdot \frac{\partial p_a}{\partial y} - \frac{\rho_m g}{\rho} \cdot \frac{\partial (z - \xi)}{\partial y} -$$

$$- g \frac{(z - \xi)}{\rho} \cdot \frac{\partial \rho_m}{\partial y} - \frac{1}{\rho} \cdot \frac{\partial q}{\partial y} + \frac{1}{\rho} \cdot \frac{\partial}{\partial z} k\rho \frac{\partial v}{\partial z} + A \cdot \nabla^2 v. \qquad (16)$$

Let us integrate further the equations of motion and continuity with respect to z, using the rule of integration of the function with variable upper and lower limits.

Let us use the following as the boundary conditions:

1. On a free surface with z = ε,

$\rho k \frac{\partial u}{\partial z} = -T_{\bar{x}0}, \; \rho k \frac{\partial v}{\partial z} = -T_{\bar{y}_0}$ is the stress of turbulent friction, with p = $p_a$

$\frac{\partial \xi}{\partial t} + u_\xi \frac{\partial \xi}{\partial x} + v_\xi \frac{\partial \xi}{\partial y} = w_\xi$ is the kinematic condition.

2. On the bottom of the sea, with z = h, $u_H = v_H = w_H = 0$, and also $\frac{\partial u}{\partial z} = \frac{\partial v}{\partial z} = T_{\bar{x}H} = T_{\bar{y}H} = 0.$

3. On the solidus curve G at the coast $c_n = w = 0$, where $c_n$ is the normal component of the flow rate.

4. On the liquidus of the curve $u = u_n$, $v = v_n$. In addition, we will consider the horizontal heat flux and flow of salt given on the liquidus. First of all, let us integrate the equation of continuity /100

$$\int_\xi^H \frac{\partial u}{\partial x} dz = \frac{\partial}{\partial x} \int_\xi^H u dz - \frac{\partial H}{\partial x} u \Big|_{z=H} + \frac{\partial \xi}{\partial x} u \Big|_{z=\xi}, \tag{17}$$

or in accordance with the boundary conditions at the bottom

$$\int_\xi^H \frac{\partial u}{\partial x} dz = \frac{\partial}{\partial x} \int_\xi^H u dz + \frac{\partial \xi}{\partial x} u \Big|_{z=\xi};$$
$$\int_\xi^H \frac{\partial v}{\partial y} dz = \frac{\partial}{\partial y} \int_\xi^H v dz + \frac{\partial \xi}{\partial y} v \Big|_{z=\xi}. \tag{18}$$

Let us introduce the new independent variable $\eta = \frac{z}{H - \xi}$. With an accuracy up to high-order infinitesimals 0 ≤ 1, and dz = (h−ε)d.

In this case

$$\int_{\xi}^{H} f dz = (H-\xi)\int_{0}^{1} f d\eta, \tag{19}$$

where f is the integrated function (in this case, u or v).

Let us designate the integral components of the flow rate used in oceanology:

$$\int_{\xi}^{H} u dz = U = \bar{u}(H-\xi);$$
$$\int_{\xi}^{H} v dz = V = \bar{v}(H-\xi), \tag{20}$$

where $\bar{u}$ and $\bar{z}$ are the average values of the velocity components. Then

$$\bar{u} = \frac{1}{H-\xi}\int_{0}^{H} u dz = \int_{2}^{1} u d\eta;$$
$$\bar{v} = \frac{1}{H-\xi}\int_{0}^{H} v dz = \int_{2}^{1} v d\eta. \tag{21}$$

Taking into account the designations employed, the equation of continuity in the integral form will have the following appearance:

$$w\Big|_{z=\xi} = \int_{\xi}^{H} \frac{\partial u}{\partial x} dz + \int_{\xi}^{H} \frac{\partial v}{\partial y} dz,$$

or

$$w\Big|_{z=\xi} = w_{\xi} = \frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} + \left[u\frac{\partial \xi}{\partial x} + v\frac{\partial \xi}{\partial y}\right]_{z=\xi}.$$

Taking into account equation (17) we will have /101

$$\frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} = \frac{\partial \xi}{\partial t}. \tag{22}$$

Let us integrate equation (22) over the area subtended by the given curve G

$$\int_{(\sigma)} \operatorname{div} c \, d\sigma = \int_{(\sigma)} \frac{\partial \xi}{\partial t} d\sigma. \tag{23}$$

Shifting from the integral with respect to the area to the integral with respect to the surface, we will have

$$\int_{(G)} c_n dL = \int_{(\sigma)} \frac{\partial \xi}{\partial t} d\sigma, \tag{24}$$

where $d\sigma$ is an element of area and dL is an element of length.

Considering that on the solidus curve $c_n = 0$ and assuming that the influx of mass and its efflux compensate one another for a rather large time interval, we will have

$$\int_{(G)} c_n dL = 0.$$

The latter is equivalent to the possibility of considering the integral motion to be nondivergent for stationary or quasistationary conditions. But this in turn makes it possible to introduce the integral stream function $\psi$

$$U = -\frac{\partial \psi}{\partial y}, \quad V = \frac{\partial \psi}{\partial x}. \tag{25}$$

In the general case however

$$\frac{\partial U}{\partial x} - \frac{\partial V}{\partial y} = \frac{\partial \xi}{\partial t}$$

the integral divergence of the velocity in the ocean is the same as in the atmosphere, in other words it is not equal to zero, although for a number of problems this difference can be disregarded.

Now let us carry out the transformation of the equations of motion in order to obtain nonlinear diagnostic and prognostic equations relative to the current function, taking into account the baroclinicity of the ocean and the inhomogeneity of the bottom relief.

Usually problems crop up in the integration of nonlinear terms, so that we shall use several approaches that will make it possible to circumvent them and (admittedly roughly) take into account the influence of nonlinear terms. We shall attempt to evaluate the possible errors which would arise in the replacement of average values of nonlinear combinations by nonlinear combinations of the corresponding average values.

Let us integrate the motion equations with respect to z from $z = \varepsilon$ to $\varepsilon = H$, letting A be independent of depth. Then, using equations (13) and (14) and adding the term $u\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z}\right) = 0,$ /102

to the left side of equation (15), we will have

$$\int_{\xi}^{H} \left(\frac{\partial u}{\partial t} + \frac{\partial u^2}{\partial x} + \frac{\partial uv}{\partial y} + \frac{\partial uw}{\partial z}\right) dz - lV = -\frac{H-\xi}{\bar{\rho}} \cdot \frac{\partial p_a}{\partial x} + \frac{\rho_m}{\bar{\rho}} g (H-\xi) \frac{\partial \xi}{\partial x} - \frac{g}{\bar{\rho}} \cdot \frac{\partial \rho_m}{\partial x} \cdot \frac{(H-\xi)^2}{2} - \frac{1}{\bar{\rho}} \int_{\xi}^{H} \frac{\partial q}{\partial x} dz - \frac{1}{\bar{\rho}} \left(k\rho \frac{\partial u}{\partial z}\right)\Big|_{z=\xi} + A \int_{\xi}^{H} \nabla^2 u dz. \tag{26}$$

Then, by adding $v\left(\frac{\partial u}{\partial x} + \frac{\partial x}{\partial y} + \frac{\partial w}{\partial z}\right) = 0,$ to the left side of equation (16), we will have

$$\int_{\xi}^{H} \left(\frac{\partial v}{\partial t} + \frac{\partial uv}{\partial x} + \frac{\partial v^2}{\partial y} + \frac{\partial vw}{\partial z}\right) dz + lU = -\frac{H-\xi}{\bar{\rho}} \cdot \frac{\partial p_a}{\partial y} + \frac{\rho_m g}{\bar{\rho}} \times (H-\xi) \frac{\partial \xi}{\partial y} - \frac{g}{\bar{\rho}} \cdot \frac{\partial \rho_m}{\partial y} \cdot \frac{(H-\xi)^2}{2} - \frac{1}{\bar{\rho}} \int_{\xi}^{H} \frac{\partial q}{\partial y} dz - \frac{1}{\bar{\rho}} \left(k\rho \frac{\partial v}{\partial z}\right)\Big|_{z=\xi} + A \int_{\xi}^{H} \nabla^2 v dz. \tag{27}$$

Here $\bar{\rho}$ is the average density value with respect to the vertical. (We can let $\rho_m/\bar{\rho} = 1$ without considerable error for the purpose of simplifying the problem.)

Now let us perform integration, taking into account the altered limits of integration and boundary conditions with respect to z.

$$\int_{\xi}^{H} \frac{\partial u}{\partial t} dz + \int_{\xi}^{H} \frac{\partial u^2}{\partial x} dz + \int_{\xi}^{H} \frac{\partial uv}{\partial y} dz + \int_{\xi}^{H} \frac{\partial uw}{\partial z} dz =$$

$$= \frac{\partial U}{\partial t} + \frac{\partial}{\partial x} \int_{\xi}^{H} u^2 dz + \frac{\partial}{\partial y} \int_{\xi}^{H} uv dz + u_{\xi} \left( \frac{\partial \xi}{\partial t} + u_{\xi} \frac{\partial \xi}{\partial x} + v_{\xi} \frac{\partial \xi}{\partial y} - w_{\xi} \right) =$$

$$= \frac{\partial U}{\partial t} + \frac{\partial}{\partial x} \int_{\xi}^{H} u^2 dz + \frac{\partial}{\partial y} \int_{\xi}^{H} uv dz. \qquad (28)$$

Here and in the following, $u\big|_{z=\xi} = u_{\xi};\ v\big|_{z=\xi} = v_{\xi},\ w\big|_{z=\xi} = w_{\xi}.$ /103

Let

$$u = \bar{u} B_1(\eta) = \bar{u} B_1; \qquad (29)$$
$$v = \bar{v} B_2(\eta) = \bar{v} B_2,$$

where $B_1$ and $B_2$ are certain functions of the vertical coordinate.

On the basis of (21) we will have

$$\bar{u} = \int_0^1 u d\eta = \int_0^1 \bar{u} B_1 d\eta = \bar{u} \int_0^1 B_1 d\eta,$$

whence

$$\int_0^1 B_1 d\eta = \bar{B}_1 = 1. \qquad (30)$$

Then

$$\overline{v} = \int_0^1 v d\eta = \int_0^1 \overline{v} B_2 d\eta = \overline{v} \int_\xi^1 B_2 d\eta,$$

whence

$$\int_0^1 B_2 d\eta = \overline{B}_2 = 1. \tag{31}$$

Then

$$\int_\xi^H u^2 dz = (H - \xi) \int_0^1 u^2 d\eta,$$

$$\int_\xi^H uv dz = (H - \xi) \int_0^1 uv d\eta.$$

Taking into account equation (29) we will have

$$\int_0^1 u^2 d\eta = \int_0^1 \overline{u}^2 B_1^2 d\eta = \overline{u}^2 \int_2^1 B_1^2 d\eta; \tag{32}$$

$$\int_0^1 uv d\eta = \int_0^1 \overline{u}\,\overline{v} B_1 B_2 d\eta = \overline{u}\,\overline{v} \int_0^1 B_1 B_2 d\eta. \tag{33}$$

Then
$$\int_{\xi}^{H} v^2 dz = (H-\xi)\int_{0}^{1} v^2 d\eta,$$
$$\int_{0}^{1} v^2 d\eta = \overline{v}^2 \int_{0}^{1} B_2^2 d\eta. \qquad (34)$$

Let $B_1 = \overline{B}_1 + B_1'$, $B_2 = \overline{B}_2 + B_2'$, /104
where $B_1'$ and $B_2'$ are the deviations from the corresponding average values $\overline{B}_1$ and $\overline{B}_2$.

In this case, taking into account the fact that $\int_{0}^{1} B_1' d\eta = 0,$ we will have

$$\int_{0}^{1} B_1^2 d\eta = 1 + \int_{0}^{1} (B_1')^2 d\eta. \qquad (35)$$

Let us designate

$$\int_{0}^{1} (B_1')^2 d\eta = \overline{(B_1')^2} = \alpha'. \qquad (36)$$

An estimate of this term may be obtained either on the basis of experimental data or approximately. For this purpose, one can give the relationship between the rate of flow and the depth in the surface and bottom layers of friction according to the Ekman spiral, and in the deep layer, proceeding on the basis of geostrophic relationships.

This term is usually disregarded in oceanological calculations, assuming that $\overline{u^2} = u^2$. However, $\alpha'$ is not equal to 0; according to rough estimates, $\alpha'$ does not exceed 0.1-0.2 on the average.

Taking equation (36) into account, we will have

$$\int_{0}^{1} B_1^2 d\eta = 1 + \alpha',$$
$$\int_{\xi}^{H} u^2 dz = (H-\xi)\,\overline{u}^2 (1+\alpha'). \qquad (37)$$

Similarly,

$$\int_0^1 B_2^2 d\eta = 1 + \beta';$$

$$\int_\xi^H v^2 dz = (H-\xi)\,\bar{v}^2\,(1+\beta'); \tag{38}$$

$$\int_0^1 B_1 B_2 d\eta = \bar{B}_1 \bar{B}_2 + \int_0^1 B_1' B_2' d\eta = 1 + \overline{B_1' B_2'}; \tag{39}$$

$$\int_\xi^H uv dz = (H-\xi)\,\overline{uv}\,(1+\gamma'), \tag{40}$$

where

$$\beta' = \overline{(B_2')^2};$$
$$\gamma = \overline{B_1' B_2'}.$$

The bar is always used as a sign of averaging. The last covariation tends toward 0 as the correlation between the components of the flow on the x and y axes decreases. In any case, $\gamma'$ cannot exceed $\alpha'$ or $\beta'$. /105

Letting $1 + \alpha' = \alpha$, $1 + \beta' = \beta$, $1 + \gamma' = \gamma$, we will have

$$\int_\xi^H u^2 dz = (H-\xi)\,\alpha\bar{u}^2;$$
$$\int_\xi^H v^2 dz = (H-\xi)\,\beta\bar{v}^2; \tag{41}$$
$$\int_\xi^H uv dz = (H-\xi)\,\gamma\bar{u}\bar{v},$$

Taking this into account, and also noting the relationship between $\bar{u}$ and U, $\bar{v}$ and V, on the basis of (20), (28), and (41), we will have

$$\int_{\xi}^{H} \frac{\partial u}{\partial t} dz + \int_{\xi}^{H} \frac{\partial u^2}{\partial x} dz + \int_{\xi}^{H} \frac{\partial uv}{\partial y} dz + \int_{\xi}^{H} \frac{\partial uw}{\partial z} = \tag{42}$$

$$= \frac{\partial U}{\partial t} + \frac{\partial}{\partial x}\left(\frac{\alpha U^2}{H-\xi}\right) + \frac{\partial}{\partial y}\left(\frac{\gamma UV}{H-\xi}\right);$$

$$\int_{\xi}^{H} \frac{\partial v}{\partial t} dz + \int_{\xi}^{H} \frac{\partial uv}{\partial x} dz + \int_{\xi}^{H} \frac{\partial v^2}{\partial y} dz + \int_{\xi}^{H} \frac{\partial vw}{\partial z} dz =$$

$$\frac{\partial V}{\partial t} + \frac{\partial}{\partial x}\left(\frac{\gamma UV}{H-\xi}\right) + \frac{\partial}{\partial y}\left(\frac{\beta V^2}{H-\xi}\right). \tag{43}$$

Further, we will say that

$$\frac{\alpha}{H-\xi} = H_1^*, \quad \frac{\beta}{H-\xi} = H_2^*, \quad \frac{\gamma}{H-\xi} = H_3^*.$$

The functions $H_1^*$, $H_2^*$, and $H_3^*$ will depend primarily on the relief of the bottom, partly on $\varepsilon$ and partly on the inhomogeneity of the vertical flow profile.

If we let $\alpha = \beta = \gamma = 1$, then

$$H_1^* = H_2^* = H_3^* = H^* = \frac{1}{H-\xi}. \tag{44}$$

In this case, we will obtain expressions which are usually employed in the consideration of nonlinear terms. Now let us integrate the remaining terms on the right hand sides of equations (26) and (27) /10

$$\int_{\xi}^{H} \frac{\partial q}{\partial x} dz = \frac{\partial}{\partial x} \int_{\xi}^{H} q dz - q_H \frac{\partial H}{\partial x};$$

$$\int_{\xi}^{H} \frac{\partial q}{\partial y} dz = \frac{\partial}{\partial y} \int_{\xi}^{H} q dz - q_H \frac{\partial H}{\partial y}. \qquad (45)$$

For viscosity terms, eliminating the intermediate calculations and assuming that

$$\frac{\partial u|_{z=\xi}}{\partial x} \cdot \frac{\partial \xi}{\partial x} = \frac{\partial u}{\partial x}\Bigg|_{z=\xi} \cdot \frac{\partial \xi}{\partial x},$$

$$\frac{\partial u|_{z=\xi}}{\partial y} \cdot \frac{\partial \xi}{\partial y} = \frac{\partial u}{\partial y}\Bigg| \cdot \frac{\partial \xi}{\partial y},$$

we will have

$$\int_{\xi}^{H} \nabla^2 u dz = \nabla^2 U + u_\xi \nabla^2 \xi + 2\left(\frac{\partial u_\xi}{\partial x} \cdot \frac{\partial \xi}{\partial x} + \frac{\partial u_\xi}{\partial y} \cdot \frac{\partial \xi}{\partial y}\right). \qquad (46)$$

Then

$$\int_{\xi}^{H} \nabla^2 v dz = \nabla^2 V + v_\xi \nabla^2 \xi + 2\left(\frac{\partial v_\xi}{\partial x} \cdot \frac{\partial \xi}{\partial x} + \frac{\partial V_\xi}{\partial y} \cdot \frac{\partial \xi}{\partial y}\right). \qquad (47)$$

On the basis of the transformations which have been carried out, the system of average depth equations of motion (with respect to vertical) will have the following form

$$\frac{\partial U}{\partial t}+\frac{\partial}{\partial x}\left(H_1^*U^2\right)+\frac{\partial}{\partial y}\left(H_3^*UV\right)-lV=-\frac{H-\xi}{\bar{\bar{\rho}}}\cdot\frac{\partial p_a}{\partial x}+$$

$$+\frac{\rho_m}{\bar{\bar{\rho}}}g\left(H-\xi\right)\frac{\partial\xi}{\partial x}-\frac{g}{2\bar{\bar{\rho}}}\left(H-\xi\right)^2\frac{\partial\rho_m}{\partial x}-\frac{1}{\bar{\bar{\rho}}}\cdot\frac{\partial p'}{\partial x}+\frac{1}{\bar{\bar{\rho}}}q_H\frac{\partial H}{\partial x}+ \qquad (48)$$

$$+\frac{T_{\overline{x0}}}{\bar{\bar{\rho}}}+A\nabla^2U+Au_\xi\nabla^2\xi+2A\left(\frac{\partial u_\xi}{\partial x}\cdot\frac{\partial x}{\partial x}+\frac{\partial u_\xi}{\partial y}\cdot\frac{\partial\xi}{\partial y}\right);$$

$$\frac{\partial V}{\partial t}+\frac{\partial}{\partial x}\left(H_3^*UV\right)+\frac{\partial}{\partial y}\left(H_2^*V^2\right)+lU=-\frac{H-\xi}{\bar{\bar{\rho}}}\cdot\frac{\partial p_a}{\partial y}+$$

$$+\frac{\rho_m}{\bar{\bar{\rho}}}g\left(H-\xi\right)\frac{\partial\xi}{\partial y}-\frac{g}{2\bar{\bar{\rho}}}\left(H-\xi\right)^2\frac{\partial\rho_m}{\partial y}-\frac{1}{\bar{\bar{\rho}}}\cdot\frac{\partial p^1}{\partial y}+\frac{1}{\bar{\bar{\rho}}}q_H\frac{\partial H}{\partial y}+$$

$$+\frac{T_{\overline{y0}}}{\bar{\bar{\rho}}}+A\nabla^2V+Av_\xi\nabla^2\xi+2A\left(\frac{\partial v_\xi}{\partial x}\cdot\frac{\partial\xi}{\partial x}+\frac{\partial v_\xi}{\partial y}\cdot\frac{\partial\xi}{\partial y}\right), \qquad (49)$$

where $p' = \int_\xi^H q dz.$

Assuming (as is done in an atmosphere) that $B_1(\eta) = B_2(\eta)$, /107 we can consider that $\alpha = \beta = \gamma$, so that

$$H_1^*=H_2^*=H_3^*=\frac{\alpha}{H-\xi}=H^*. \qquad (50)$$

In this case the averaged equations of motion can be rewritten as follows:

$$\frac{\partial U}{\partial t}+H^*\left(U\frac{\partial U}{\partial x}+V\frac{\partial U}{\partial y}\right)+H^*U\left(\frac{\partial U}{\partial x}+\frac{\partial V}{\partial y}\right)+$$

$$+U\left(U\frac{\partial H^*}{\partial x}+V\frac{\partial H^*}{\partial y}\right)-lV=-\frac{H-\xi}{\bar{\bar{\rho}}}\cdot\frac{\partial p_a}{\partial x}+g\frac{\rho_m}{\bar{\bar{\rho}}}\left(H-\xi\right)\frac{\partial\xi}{\partial x}-$$

$$-\frac{g}{2\bar{\bar{\rho}}}\left(H-\xi\right)^2\frac{\partial\rho_m}{\partial x}-\frac{1}{\bar{\bar{\rho}}}\cdot\frac{\partial p'}{\partial x}+\frac{1}{\bar{\bar{\rho}}}q_H\cdot\frac{\partial H}{\partial x}+\frac{T_{\overline{x0}}}{\bar{\bar{\rho}}}+A\nabla^2U+$$

$$+2A\left(\frac{\partial u_\xi}{\partial x}\cdot\frac{\partial\xi}{\partial x}+\frac{\partial u_\xi}{\partial y}\cdot\frac{\partial\xi}{\partial y}\right)+Au_\xi\nabla^2\xi; \qquad (51)$$

$$\frac{\partial V}{\partial t}+H^*\left(U\frac{\partial V}{\partial x}+V\frac{\partial V}{\partial y}\right)+H^*V\left(\frac{\partial U}{\partial x}+\frac{\partial V}{\partial y}\right)+$$

$$+V\left(U\frac{\partial H^*}{\partial x}+V\frac{\partial H^*}{\partial y}\right)+lU=\frac{H-\xi}{\bar{\rho}}\cdot\frac{\partial p_a}{\partial y}+\frac{\rho_m}{\bar{\rho}}g(H-\xi)\times$$

$$\times\frac{\partial \xi}{\partial y}-\frac{g}{2\bar{\rho}}(H-\xi)^2\frac{\partial \rho_m}{\partial y}-\frac{1}{\bar{\rho}}\cdot\frac{\partial p'}{\partial y}+\frac{1}{\bar{\rho}}q_H\cdot\frac{\partial H}{\partial y}+\frac{T_{\overline{y0}}}{\bar{\rho}}+$$

$$+A\nabla^2 V+2A\left(\frac{\partial v_\xi}{\partial x}\cdot\frac{\partial \xi}{\partial x}+\frac{\partial v_\xi}{\partial y}\cdot\frac{\partial \xi}{\partial y}\right)+Av_\xi\nabla^2\xi. \tag{52}$$

By combining equation (22) with the above equations we will obtain a system of three equations for finding three unknown functions, U, V, and $\varepsilon$ under the condition that the values p', $q_H$, H, $u_\xi$, $v_\xi$ and $T_{\overline{x0}}$, $T_{\overline{y0}}$ are given or calculated on the basis of given external parameters. The accomplishment of the solution of such a system of equations may be achieved by one of the methods of solution of complete equations, similar to that which was done in [2] for a system of equations for the atmosphere.

Let us also consider the non-divergent model in which the divergence of the total flux is equal to 0. Using equations (51) and (52), we will carry out the operation of divergence. To do this /108 we shall differentiate equation (51) with respect to x, equation (52) with respect to y and combine them. As a result we will have:

$$\frac{\partial D}{\partial t}+2H^*\left(U\frac{\partial D}{\partial x}+V\frac{\partial D}{\partial y}\right)+H^*D^2+2D\left(U\frac{\partial H^*}{\partial x}+V\frac{\partial H^*}{\partial y}\right)+$$

$$+2H^*\frac{\partial U}{\partial y}\cdot\frac{\partial V}{\partial x}+H^*\left(\frac{\partial U}{\partial x}\right)^2+H^*\left(\frac{\partial V}{\partial y}\right)^2+\left(U\frac{\partial u}{\partial x}+V\frac{\partial U}{\partial y}\right)\times$$

$$\times\frac{\partial H^*}{\partial x}+\left(U\frac{\partial V}{\partial x}+V\frac{\partial V}{\partial y}\right)\frac{\partial H^*}{\partial y}+U^2\frac{\partial^2 H^*}{\partial x^2}+V^2\frac{\partial^2 H^*}{\partial y^2}+U\frac{\partial H^*}{\partial x}\cdot\frac{\partial U}{\partial x}+$$

$$+V\frac{\partial H^*}{\partial x}\cdot\frac{\partial U}{\partial y}+V\frac{\partial H^*}{\partial y}\cdot\frac{\partial V}{\partial y}+U\frac{\partial H^*}{\partial y}\cdot\frac{\partial V}{\partial x}-l\Omega_z+$$

$$+2UV\frac{\partial^2 H^*}{\partial x\cdot\partial y}-Vl_x+Ul_y=F_1(x,y), \tag{53}$$

where

$$\Omega_z=\frac{\partial V}{\partial x}-\frac{\partial U}{\partial y}.$$

$$
\begin{aligned}
F_1(x, y) = & -\frac{H-\xi}{\xi}\nabla^2 p_a + g\frac{\rho_m}{\bar\rho}(H-\xi)\nabla^2\xi - \frac{1}{\bar\rho}\nabla^2 p' - \\
& - \frac{g}{2\bar\rho}(H-\xi)^2\nabla^2\rho_m + \frac{\partial}{\partial x}(H-\xi)\cdot\left(\frac{\rho_m}{\bar\rho} g\frac{\partial\xi}{\partial x} - \frac{1}{\bar\rho}\cdot\frac{\partial p_a}{\partial x} - \right. \\
& \left. - \frac{H-\xi}{\bar\rho} g\frac{\partial\rho_m}{\partial x}\right) + \frac{\partial}{\partial y}(H-\xi)\cdot\left(\frac{\rho_m}{\bar\rho} g\frac{\partial\xi}{\partial y} - \frac{1}{\bar\rho}\cdot\frac{\partial p_a}{\partial y} - \frac{H-\xi}{\bar\rho} g\frac{\partial\rho_m}{\partial y}\right) + \\
& + \frac{\partial\bar\rho}{\partial x}\left[\frac{H-\xi}{\bar\rho^2}\cdot\frac{\partial p_a}{\partial x} + \frac{g}{2\bar\rho^2}(H-\xi)^2\frac{\partial\rho_m}{\partial x} - \frac{q_H}{\bar\rho^2}\cdot\frac{\partial H}{\partial x} + \frac{1}{\bar\rho^2}\cdot\frac{\partial p'}{\partial x} - \right. \\
& \left. - \frac{T_{\bar{x}0}}{\bar\rho^2}\right] + \frac{\partial\bar\rho}{\partial y}\left[\frac{H-\xi}{\bar\rho^2}\cdot\frac{\partial p_a}{\partial y} + \frac{g}{2\bar\rho^2}(H-\xi)^2\frac{\partial\rho_m}{\partial y} - \frac{q_H}{\bar\rho^2}\cdot\frac{\partial H}{\partial y} + \right. \\
& \left. + \frac{1}{\bar\rho^2}\cdot\frac{\partial p'}{\partial y} - \frac{T_{\bar{y}0}}{\bar\rho^2}\right] + \frac{q_H}{\bar\rho}\nabla^2 H + \frac{1}{\bar\rho}\left(\frac{\partial H}{\partial x}\cdot\frac{\partial q_H}{\partial y} + \frac{\partial H}{\partial y}\cdot\frac{\partial q_H}{\partial y}\right) + \\
& + \frac{1}{\bar\rho}\left(\frac{\partial T_{\bar{x}0}}{\partial x} + \frac{\partial T_{\bar{y}0}}{\partial y}\right) + A\left(\frac{\partial}{\partial x}\nabla^2 U + \frac{\partial}{\partial y}\nabla^2 V\right) + A(M_{x\xi} + M_{y\xi}).
\end{aligned} \tag{54}
$$

Here

$$
M_{x\xi} = \frac{\partial}{\partial x}\left[2\left(\frac{\partial u_\xi}{\partial x}\cdot\frac{\partial\xi}{\partial x} + \frac{\partial u_\xi}{\partial y}\cdot\frac{\partial\xi}{\partial y}\right) + u_\xi\nabla^2\xi\right];
$$

$$
M_{y\xi} = \frac{\partial}{\partial y}\left[2\left(\frac{\partial v_\xi}{\partial x}\cdot\frac{\partial\xi}{\partial x} + \frac{\partial v_\xi}{\partial y}\cdot\frac{\partial\xi}{\partial y}\right) + v_\xi\nabla^2\xi\right].
$$

The condition of nondivergence D = 0 makes it possible to introduce an integral stream function so that $U = -\frac{\partial\psi}{\partial y}$, $V = \frac{\partial\psi}{\partial x}$.

Then /109

$$
\Omega_z = \nabla^2\psi,
$$

$$
\frac{\partial}{\partial x}\nabla^2 U + \frac{\partial}{\partial y}\nabla^2 V = 0.
$$

As a result, equation (53) will have the form

$$
\begin{aligned}
& l\nabla^2\psi - 2H^*(\psi_{xy}^2 - \psi_{xx}\psi_{yy}) + 2H_x^*(\psi, \psi_y) - 2H_y^*(\psi, \psi_x) - \\
& - H_{xx}^*\psi_y^2 - H_{yy}^*\psi_x^2 + 2H_{xy}^*\psi_x\psi_y + \psi_x l_x + \psi_y l_y = \frac{H-\xi}{\bar\rho}\nabla^2 p_a - \\
& - g(H-\xi)\nabla^2\xi + \frac{1}{\rho}\nabla^2 p' + \frac{g}{2\rho}(H-\xi)^2\nabla^2\rho_m - \\
& - (H-\xi)_x\left(g\xi_x - \frac{1}{\bar\rho}p_{a,x} - \frac{H-\xi}{\bar\rho}g\rho_{m,x}\right) - (H-\xi)_y \times \\
& \times\left(g\xi_y - \frac{1}{\rho}p_{a,y} - (H-\xi)\frac{g}{\rho}\rho_{m,y}\right) - \bar\rho_x\left[\frac{H-\xi}{\bar\rho^2}p_{a,x} + \frac{g}{2\bar\rho^2}\times\right.
\end{aligned}
$$

$$\times (H-\xi)^2 \bar{\rho}_{m,x} - \frac{q_H}{\bar{\rho}^2} H_x + \frac{1}{\bar{\rho}^2} p'_x - \frac{T_{\bar{x}0}}{\bar{\rho}^2}\Big] - \bar{\rho}_y \Big[\frac{H-\xi}{\bar{\rho}^2} p_{a,y} +$$

$$+ \frac{g}{2\bar{\rho}^2} (H-\xi)^2 \rho_{m,y} - \frac{q_H}{\bar{\rho}^2} H_y + \frac{1}{\bar{\rho}^2} p'_x - \frac{T_{\bar{y}0}}{\bar{\rho}^2}\Big] - \frac{q_H}{\bar{\rho}} \nabla^2 H -$$

$$- \frac{1}{\bar{\rho}} (H_x q_{H,x} + H_y q_{H,y}) - \frac{1}{\bar{\rho}} \left(T_{\bar{x}_0,x} + T_{\bar{y}_0,y}\right) - A(M_{x\xi} + M_{y\xi}). \qquad (55)$$

Here the subscripts x and y represent the corresponding differentiation. For example,

$$\psi_{xy} = \frac{\partial^2 \psi}{\partial x \partial y}, \quad q_{H,x} = \frac{\partial q_H}{\partial x}, \quad T_{\bar{y}_0,y} = \frac{\partial T_{\bar{y}0}}{\partial y}.$$

If we do not take the inhomogeneity of the ocean according to depth into account, equation (55) is simplified considerably.

$$l\nabla^2\psi - 2H^*(\psi_{xy}^2 - \psi_{xx}\psi_{yy}) + \psi_x l_x + \psi_y l_y = F_2(x, y). \qquad (56)$$

Here the right hand side depends on the additional conditions we impose. Thus, if the ocean is homogeneous and we are considering a barotropic model, by excluding the potential of the external tide-forming forces

$$\frac{1}{\bar{\rho}} \nabla^2 p_a = -g\nabla^2\xi, \quad g\xi_x = -\frac{1}{\bar{\rho}} p_{a,x},$$

$$g\xi_y = -\frac{1}{\bar{\rho}} p_{a,y}$$

We will have /110

$$F_2(x, y) = -\frac{1}{\bar{\rho}} \left(T_{\bar{x}0,x} + T_{\bar{y}0,y}\right) - A(M_{x\xi} + M_{y\xi}).$$

For a sea which is uniform with respect to depth, taking into account the baroclinicity and disregarding the potential of the tide-forming forces, we will have

$$F_2(x, y) = \frac{1}{\bar{\rho}} \nabla^2 \bar{p}' + \frac{g}{2\bar{\rho}} (H - \xi)^2 \nabla^2 \rho_m - \frac{(H-\xi)}{\bar{\rho}} g \left(\xi_x \rho_{m,x} + \xi_y \rho_{m,y}\right) -$$

$$- \bar{\rho}_k \left[\frac{H-\xi}{\bar{\rho}^2} p_{a,x} + \frac{g}{2\bar{\rho}^2} (H-\xi)^2 \rho_{m,x} + \frac{1}{\bar{\rho}^2} p'_x - \frac{T_{\bar{x}0}}{\bar{\rho}^2}\right] -$$

$$- \bar{\rho}_y \left[\frac{H-\xi}{\bar{\rho}^2} p_{a,y} + \frac{g}{2\bar{\rho}^2} (H-\xi)^2 \rho_{m,y} + \frac{1}{\bar{\rho}^2} p'_x - \frac{T_{\bar{y}0}}{\bar{\rho}^2}\right] -$$

$$- \frac{1}{\bar{\rho}} \left(T_{\bar{x}0,x} + T_{\bar{y}0,y}\right) - A\left(M_{x\xi} + M_{y\xi}\right).$$

An equation of the type of (55) or (56) is quite well known in dynamic meteorology as a balance equation. It is an equation of the Monge - Ampere type relative to the stream function. This same equation can be used as a diagnostic one for finding (for example) the level of p' if we know the stream function and all of the other terms that go into equation (55).

In solving an equation of this type, there are a number of problems, of which the most important is the difference in the iteration process when the conditions of ellipticity are violated. As far as we know, such an equation cannot be used for solving oceanological problems. However, it is a quite good diagnostic equation and may be widely used in oceanology in solving stationary problems of oceanic circulation. Detailed information on methods of solving this type of equation can be found in [4].

It must be pointed out that the unnecessary cumbersome nature of the right-hand side of equation (55) is the result of the fact that we are dividing the pressure gradient by means of expression (11) into several components. In the practical realization of this task, it may be disregarded if we integrate the right hand side of equations (1) and (2) directly.

In order to solve a nonstationary and nonlinear problem which may have prognostic significance, we turn again to the equations of motion (51) and (52) integrated with respect to vertical and carry out the vortex operation on them.

Differentiating equation (52) with respect to x, equation (51) with respect to y, we calculate the former from the second equation. In this instance, considering that

$$\frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} = D = 0, \quad \frac{\partial V}{\partial x} - \frac{\partial U}{\partial y} = \Omega_z,$$

we will have /111

$$\frac{\partial\Omega_z}{\partial t}+H^*U\frac{\partial\Omega_z}{\partial x}+H^*V\frac{\partial\Omega_z}{\partial y}+2\frac{\partial H^*}{\partial x}U\Omega_z+2\frac{\partial H^*}{\partial y}V\Omega_z+ \tag{57}$$

$$+UV\left(\frac{\partial^2H^*}{\partial x^2}-\frac{\partial^2H^*}{\partial y^2}\right)+(V^2-U^2)\frac{\partial^2H^*}{\partial x\cdot\partial y}+l_xU+l_yV=F_3(x,y);$$

$$F_3(x,y)=\frac{1}{\bar\rho}\left(\frac{\partial T_{\bar y_0}}{\partial x}-\frac{\partial T_{\bar x_0}}{\partial y}\right)+A\left(\frac{\partial}{\partial x}\nabla^2V-\frac{\partial}{\partial y}\nabla^2U\right)+$$

$$+A(M_{x\xi}-M_{y\xi})+\frac{1}{\bar\rho}(p_a,H-\xi)+\frac{1}{\bar\rho^2}(H-\xi)\cdot(\bar\rho,p_a)-$$

$$-\frac{\rho_m}{\bar\rho}g(\xi,H)+\frac{(H-\xi)g}{\bar\rho}(\bar\rho_m,H-\xi)+\frac{g}{2\bar\rho^2}(H-\xi)^2\cdot(\bar\rho,\rho_m)+$$

$$+\frac{1}{\bar\rho^2}(\bar\rho,p')+\frac{1}{\bar\rho}(q_H,H)+\frac{1}{\bar\rho^2}q_H(H,\bar\rho)+\frac{1}{\bar\rho^2}\times$$

$$\times\left(T_{\bar x_0}\frac{\partial\bar\rho}{\partial y}-T_{\bar y_0}\frac{\partial\bar\rho}{\partial x}\right). \tag{58}$$

Here, as before, the Jacobian of the form $A,B$ indicates

$$A,B=\frac{\partial A}{\partial x}\cdot\frac{\partial B}{\partial y}-\frac{\partial A}{\partial y}\cdot\frac{\partial B}{\partial x}.$$

In addition, we use the following condition here:

$$(\xi,H-\xi)=(\xi,H),$$

$$M_{x\xi}=\frac{\partial}{\partial x}\left[2\frac{\partial v_\xi}{\partial x}\cdot\frac{\partial\xi}{\partial x}+\frac{\partial v_\xi}{\partial y}\cdot\frac{\partial\xi}{\partial y}-v_\xi\nabla^2\xi\right];$$

$$M_{y\xi}=\frac{\partial}{\partial y}\left[2\frac{\partial u_\xi}{\partial x}\cdot\frac{\partial\xi}{\partial x}+\frac{\partial u_\xi}{\partial y}\cdot\frac{\partial\xi}{\partial y}\right)+u_\xi\nabla^2\xi\right].$$

Introducing the stream function $U=-\frac{\partial\psi}{\partial y},V=\frac{\partial\psi}{\partial x}$, on the basis of equation (57) we will have

$$\nabla^2 \frac{\partial\psi}{\partial t} = -H^*(\psi, \nabla^2\psi) + 2\nabla^2\psi(\psi, H^*) - \psi_y\psi_x(H^*_{xx} - H^*_{yy}) +$$

$$+ H^*_{xy}(\psi_x^2 - \psi_y^2) - l_x\psi_y + l_y\psi_x + A\nabla^4\psi + F_4(x, y). \tag{59}$$

Here /112

$$F_4(x, y) = \frac{1}{\bar\rho}\left(T_{\bar{y}_0, x} - T_{\bar{x}_0, y} + A(M_{x\xi} - M_{y\xi}) +\right.$$

$$+ \frac{1}{\bar\rho}(p_a, H - \xi) + \frac{1}{\bar\rho^2}(H - \xi)\cdot(\vec{\rho}, p_a) - g(\xi, H) +$$

$$+ \frac{(H - \xi)g}{\bar\rho}(\rho_m, H - \xi) + \frac{g}{2\bar\rho^2}(H - \xi)^2\cdot(\bar\rho, \rho_m) + \frac{1}{\bar\rho^2}(\bar\rho, p') +$$

$$+ \frac{1}{\bar\rho}(q_H, H) + \frac{1}{\bar\rho^2}q_H(H, \bar\rho) + \frac{1}{\bar\rho^2}\left(T_{\bar{x}_0}\bar\rho_y - T_{y_0}\bar\rho_x\right);$$

$$\frac{\partial}{\partial x}\nabla^2 V - \frac{\partial}{\partial y}\nabla^2 U = \nabla^4\psi = \frac{\partial^4\psi}{\partial x^4} + 2\frac{\partial^4\psi}{\partial x^2\cdot\partial y^2} + \frac{\partial^4\psi}{\partial y^4}.$$

Equation (59) is prognostic. This is a Poisson equation relative to the tendency of the stream function. From it one can obtain somewhat simpler versions.

Thus, if we assume that the sea is uniform with respect to depth, consider the barotropic instance and do not take into account the potential of the tide-forming forces, this equation is simplified considerably and assumes the following form:

$$\nabla^2 \frac{\partial\psi}{\partial t} = -H^*(\psi, \nabla^2\psi) - l_x\psi_x + l_y\psi_x + A\nabla^4\psi + A(M_{x\xi} - M_{y\xi}) +$$

$$+ \frac{1}{\bar\rho}\left(\frac{\partial T_{\bar{y}_0}}{\partial x} - \frac{\partial T_{\bar{x}_0}}{\partial x}\right). \tag{60}$$

If we consider the process to be stationary and discard the nonlinear terms and the terms $M_{y\xi}$ and $M_{x\xi}$, we will obtain an equation which usually is employed in oceanology in calculating the stream function for the stationary case in a linear approximation [6]. Here, however, it is clear how valuable such simplifications are for such a solution of the problem.

Equations (59) or (60) can be used also for solving the stationary problem if we use the method of determination which was discussed in detail in [5]. It has already been employed in solving a nonlinear stationary problem of circulation of an inhomogeneous barotropic ocean.

It seems more convenient to us to adopt a solution of the stationary problem based on equation (55) or its simplified versions, after which it is necessary to solve the nonstationary problem using equation (59), i.e., the same sequence is observed as in meteorology in putting together a system for precalculation employing quasisolenoidal models.

The actual numerical experiments involved in the solution of the system of equations that is obtained are of interest in themselves and are not discussed here.

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# THE PROBLEM OF THE INFLUENCE OF OCEAN CURRENTS ON FREE INTERNAL GRAVITY WAVES /114

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Internal free gravity waves arise as the reaction of stably stratified heterogeneous fluid to external energy influences. They transport energy from the region of initial excitation into the surrounding space, attempting to return the fluid to the original state of equilibrium.

In the majority of theoretical studies of internal free gravity waves in the ocean, work proceeded on the assumption that they are minor harmonic oscillations of an ideal incompressible fluid around some equilibrium state. The state of rest is usually assumed to be the latter. In this case, the system of equations of hydromechanics, describing the unexcited state of equilibrium, is reduced to one equation of statics. This choice of the basic state is equivalent to neglecting in linearized equations excitations of convective terms in comparison with local changes. V. Krauss [5] notes that this operation is inadmissible in a study of tidalinternal waves. A similar situation occurs in the study of other forms of internal gravity waves whose phase velocities are comparable to the velocities of the marine current that occur in the original state of equilibrium.

Inasmuch as the range of phase velocities of internal gravity waves in the ocean is quite broad, and some average transfer of water is more correct for all regions of the world ocean, rather than the exception, it is suggested that in order to explain many aspects of the dynamics of internal gravity waves it is necessary to take into account the marine currents (basic flow). The latter can produce significant changes in the frequency of internal waves all the way to development of dynamic instability of oscillation.

The present article presents several notions regarding the dependence of the parameters of the free internal gravity waves on the characteristics of stationary marine currents; the necessary conditions for existence of internal gravity waves are obtained, and the phenomenon of abrupt changes in phase of internal oscillation with depth that is frequently observed when carrying out natural observations is explained. The article also /115
deals with the problem of errors in the determination of the true periods of internal waves on the basis of observations of

hydrological elements used as indicators of internal oscillations. These errors are caused by the existence of a basic current and are produced by the Doppler effect.

1. For the case of an incompressible heterogeneous fluid, whose initial state is the state of rest, the precise lower limit of the periods of free internal gravity waves was first given by P. Groen [16]. Later, assuming the same basic state of equilibrium, estimates of the frequencies of the progressive harmonic free internal gravity waves were carried out in [2, 6, 9, 10, 15, 17].

Thus, for example, in the case of a compressible fluid A. S. Monin and A. M. Obukhov [9, 10] showed that the frequencies of free gravity waves are comprised within the interval

$$l^2 \leqslant \sigma^2 < g\gamma a^{-2},$$

where l is the Coriolis parameter;
$\sigma$ is the frequency of the oscillation;
g is the acceleration caused by the force of gravity;
a is the speed of sound;
$\gamma = (\varkappa - 1) g + \frac{da^2}{dz}$ — is the thermal stability parameter;
$\kappa$ is the index of polytropy;
z is the vertical coordinate directed upward,

Since in adiabatic processes $\gamma = a^2\Gamma$ (here $\Gamma = -\left(\frac{1}{\rho_0} \cdot \frac{d\rho_0}{dz} + \frac{g}{a^2}\right)$ is the stability according to Sverdrup-Hesselberg, $\rho_0$ is the density in the unexcited state), by introducing the Vyaisyal-Brent frequency $N = \sqrt{g\Gamma}$ and by making the transition to the incompressible fluid ($a \to \infty$), we will find that the frequencies of the waves in question in the ocean will satisfy the inequality elsewhere.

The author of [2] studied the case of isothermal atmosphere in the absence of Coriolis forces and showed that all frequencies of free gravity waves are limited by the frequency

$$\sigma_0 = \sqrt{(\varkappa - 1) g \varkappa^{-1} h^{-1}},$$

where h is the height of the atmosphere.

In the general case the altitude of the equivalent homogeneous atmosphere is linked to the speed of sound a by the relation

$h(z)=a^2\varkappa^{-1}g^{-1}$, for an isothermal atmosphere $\gamma=(\varkappa-1)g$.

In an incompressible fluid, obviously, this case corresponds to constancy of the gradient of the logarithm of the density regardless of altitude, and a number of frequencies of gravity waves have their upper limit at the frequency

$$N=\sqrt{-g\frac{d}{dz}\ln\rho_0}=\text{const.}$$

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We shall show that the characteristics of the internal gravity waves, considered to be small oscillations, must depend upon the properties of the original state of equilibrium.

We will assume that the ocean constitutes a layer of an ideal, incompressible stably stratified horizontally infinite fluid with a thickness h. We will assume that the density of this layer $\rho_0$, as well as the velocity $u_0$ and the direction of the horizontal mass transfer in it are functions of the vertical coordinate z alone. Let us orient the axis z of the rectangular system of coordinates vertically upward, and the axes x and y horizontally. Let us establish the origin of the coordinates on the flat horizontal bottom of the sea. We will use $\beta(z)$ to represent the angle between the positive direction of the x axis and the direction of mass transfer in any fixed horizon in the layer. We will say that the excitation in the fluid is caused by a progressive free internal gravity wave, propagating at an angle $\alpha$ to the positive direction of the x axis. We will consider the internal oscillations to be minor harmonic excitations of three components of velocity, pressure and density relative to the basic state of equilibrium. We will assume that

$$r'=r(z)\exp[i(\sigma t-kx-sy)],$$

where $r'$ is any one of the five excited hydrodynamic elements;
- $r$ is a complex amplitude factor;
- $k$ and $s$ are components of the horizontal wave number, with $\alpha=\text{arc tan } s/k$;
- $t$ = time;
- $i$ = imaginary unit.

Then, relative to the amplitude of the vertical velocity of the internal wave w, we will have the usual homogeneous linear differential equation of the second order.[1]

$$
\begin{aligned}
&\frac{d^2w}{dz^2} - \left\{\Gamma - \frac{l}{l^2 - m^2(c-\bar{u})^2}\left[im\frac{d\bar{v}}{dz} + \frac{il}{(c-\bar{u})}\cdot\frac{d\bar{u}}{dz}\right]\right\}\frac{dw}{dz} - \\
&- \frac{m^2}{l^2 - m^2(c-\bar{u})^2}\left\{N^2 - (c-\bar{u})\left[m^2(c-\bar{u}) - \frac{1}{\rho_0}\frac{d}{dz}\left(\rho_0\frac{d\bar{u}}{dz}\right)\right] - \right. \\
&\left. - \frac{il}{m}\left[\frac{1}{\rho_0}\frac{d}{dz}\left(\rho_0\frac{d\bar{v}}{dz}\right) + \frac{1}{(c-\bar{u})}\cdot\frac{d\bar{u}}{dz}\cdot\frac{d\bar{v}}{dz}\right]\right\}w = 0,
\end{aligned}
\tag{1}
$$

$$
\begin{aligned}
\bar{u} &= u_0\cos(\alpha-\beta); \\
\bar{v} &= u_0\sin(\alpha-\beta); \\
c &= \sigma m^{-1}.
\end{aligned}
$$

The boundary conditions for equation (1) are written in the form /117

$$w(0) = w(H) = 0. \tag{2}$$

From (1), under the condition that l = 0, we will have

$$\frac{d}{dz}\left(\rho_0\frac{dw}{dz}\right) - \left[\rho_0 m^2 + \frac{g}{(c-\bar{u})^2}\frac{d\rho_0}{dz} - \frac{1}{(c-\bar{u})}\frac{d}{dz}\left(\rho_0\frac{d\bar{u}}{dz}\right)\right]w = 0. \tag{3}$$

---

[1]This equation can be obtained as a result of simple transformations of the equations that are given in the monograph of V. Krauss [5].

In the following it will be assumed that the function $\bar{u}$ has continuous derivatives up to the second order inclusive, and the function $\rho_0$ has a continuous first derivative within the layer $[0, H]$.

The conclusion regarding the low period of internal waves in the presence of a stationary basic flow can be obtained most simply from the equation for the deviation $\xi$ of the particles of the fluid from the equilibrium position, associated with the amplitude of the vertical velocity w by the relationship

$$w(z) = \xi(z)\, im\,(c - \bar{u}). \qquad (4)$$

From (3) and (4) we will obtain the equation relative to $\xi$

$$\frac{d^2\xi}{dz^2} - \left[\Gamma + \frac{2}{(c-\bar{u})} \cdot \frac{d\bar{u}}{dz}\right]\frac{d\xi}{dz} + \left[\frac{N^2}{(c-\bar{u})^2} - m^2\right]\xi = 0. \qquad (5)$$

Equation (5) must be viewed with homogeneous boundary conditions $\xi(0) = \xi(h) = 0$.

To determine the lower limit of the free internal gravitational waves, we will use the method of P. Groen[2] [16], applying it to equation (5). Inasmuch as the function $\xi$ within the interval is assumed to be not exactly equal to zero and continuously doubly differentiable under the established boundary conditions in accordance with the Rolletheorem, it must reach the extreme value in this interval. In this case, there is at least one level $z_j$ for which

$$\left.\frac{d\xi}{dz}\right|_{z=z_j} = 0; \quad \left.\frac{1}{\xi}\frac{d^2\xi}{dz^2}\right|_{z=z_j} < 0.$$

[2]The same method was used by M. Yasui [20] to study the conditions of stability of internal waves propagating in a frontal zone of a horizontally inhomogeneous ocean.

Consequently, according to equation (5), for such levels the inequality (6) is valid

$$N^2(c-\bar{u})^{-2}-m^2>0. \tag{6}$$

In obtaining inequality (6), c was assumed to be a real quantity which has the meaning of the phase velocity of an internal wave.

Taking into account that the period of the internal wave

$\tau=2\pi(mc)^{-1}$ from inequality (6) we will obtain the estimate

$$\tau>\frac{2\pi}{N}\left|1-\frac{\bar{u}}{c}\right|.$$

From this it follows that the inequality /118

$$\tau>\tau_0\left|1-\frac{\bar{u}}{c}\right|,$$

is all the more valid, where $\tau_0=2\pi N_0^{-1}$ is the Vyaisyal period.

Here $N_0=\max\limits_{0<z<H} N(z)$. Consequently, in the presence of the basic current, there is no exact lower limit for the free internal gravity waves. The actual period of these waves may be greater than the Vyaisyal or less than it, depending on what sign the projection of the velocity of the stationary flow in the direction of the propagation of the wave has. In the layer of coincidence ($c=\bar{u}$) the period of the internal waves $\tau\to+0$. The latter statement coincides in meaning with the conclusion of V. Krauss [5] that at a critical depth, i.e., on a level corresponding to the layer of coincidence, the internal waves will disappear.

2. Using considerations analogous to those employed in deriving inequality (6) in conjunction with equation (3), we reach the inequation (7).

$$m^2<\frac{N^2}{(c-\bar{u})^2}+\frac{1}{\rho_0(c-\bar{u})}\frac{d}{dz}\left(\rho_0\frac{d\bar{u}}{dz}\right). \tag{7}$$

Obviously, inequality (7) may be satisfied only in the case when

$$N^2>\rho_0^{-1}(\bar{u}-c)\frac{d}{dz}\left(\rho_0\frac{d\bar{u}}{dz}\right). \tag{8}$$

Consequently, the internal waves with a given phase velocity in the presence of stationary currents in a fluid may only exist if there is at least one layer for which inequality (8) is satisfied. Note that when $\bar{u}$ = const (in the partial case, $\bar{u}$ = 0) from inequality (8) we obtain the known condition of existence of internal waves, to wit: $N^2>0$, i.e., if the basic state of equilibrium is a state of uniform movement (or a state of rest), the internal waves can exist only under the condition that the inhomogeneous fluid being studied contains layers in which the density decreases with depth.

3. Let us examine the question of the limiting frequencies of internal free gravity waves from the standpoint of the intrinsic values of the equation (1). For the sake of simplicity we will let $\alpha = \beta = 0$ (plane motion). Then equation (1) is written in the form

$$\frac{d^2w}{dz^2} - \left\{\Gamma - \frac{l^2}{(c-u_0)\left[l^2 - m^2(c-u_0)^2\right]}\frac{du_0}{dz}\right\}\frac{dw}{dz} - \frac{m^2}{l^2 - m^2(c-u_0)^2} \times$$
$$\times \left\{N^2 - (c-u_0)\left[m^2(c-u_0) - \frac{1}{\rho_0}\frac{d}{dz}\left(\rho_0\frac{du_0}{dz}\right)\right]\right\} w = 0. \quad (9)$$

In order to obtain the dispersion equation, we will let /119

$$w = w_n \sin\theta z, \quad \text{where} \quad w_n = \text{const}. \quad (10)$$

Then the boundary conditions (2) will be satisfied at

$$\theta = \frac{n\pi}{H},$$

where $n = 1, 2 \ldots$ represent the modes of the internal waves
$\theta = \theta(n)$ is the vertical wave number.

Substituting (10) into (9), we will obtain

$$\theta^2 \sin\theta z + \left\{\Gamma - \frac{l^2}{(c-u_0)\left[l^2 - m^2(c-u_0)^2\right]}\frac{du_0}{dz}\right\}\theta\cos\theta z + \frac{m^2}{l^2 - m^2(c-u_0)^2} \times$$
$$\times \left[N^2 - m^2(c-u_0)^2 + \rho_0^{-1}(c-u_0)\frac{d}{dz}\left(\rho_0\frac{du_0}{dz}\right)\right]\sin\theta z = 0. \quad (11)$$

Let us examine those levels $z = z_j^*$ for which $\cos\theta z=0$, i.e., $z_j^* = Hn^{-1}$ $(j+1/2)$. Inasmuch as we are only interested in $z_j^* \in (0,H)$, for each fixed n we will have $j = 0, 1, 2, \ldots n - 1$.

For levels $z_j^*$ equation (11) will be written in the form

$$m^2c^2\left(1-\frac{u_0}{c}\right)^2(\theta^2+m^2)=\theta^2l^2+m^2\left[N^2+\rho_0^{-1}(c-u_0)\times\right.$$
$$\left.\times\frac{d}{dz}\left(\rho_0\frac{du_0}{dz}\right)\right].$$

Hence,

$$\sigma^2=\frac{l^2+\frac{1}{n^2}\left(\frac{2H}{\lambda}\right)^2\left[N^2+\rho_0^{-1}(c-u_0)\frac{d}{dz}\left(\rho_0\frac{du_0}{dz}\right)\right]}{\left[1+\frac{1}{n^2}\left(\frac{2H}{\lambda}\right)^2\right]\left(1-\frac{u_0}{c}\right)^2}, \tag{12}$$

where $\lambda=2\pi m^{-1}$ is the length of the internal wave.

The right hand side of equation (12) is positive with respect to inequality (8).

If $u_0 \equiv 0$, we can find from equation (12) with a high degree of accuracy that the frequency of rather long waves $\sigma\to 1$, i.e., approaches the frequency of the inertial oscillations, while the frequency of very short waves $\sigma\to N$, i.e., approaches the Vyaisyal-Brent frequency.

In the absence of currents in a horizontally homogeneous ocean, the frequency of the internal gravitational waves is invariant relative to the direction of their propagation. It is easy to see that in the presence of the horizontal flow it depends to a large extent on the direction of the current, its velocity, and the direction of propagation of the waves. In fact, in the presence of a basic flow, for rather long waves we will obtain from equation (12) /120

$$\sigma^2\to l^2\left(1-\frac{u_0}{c}\right)^{-2};$$

or

$$\tau \rightarrow \frac{2\pi}{l}\left|1-\frac{u_0}{c}\right|,$$

and for very short waves

$$\sigma^2 \rightarrow \left[N^2+\rho_0^{-1}(c-u_0)\frac{d}{dz}\left(\rho_0\frac{du_0}{dz}\right)\right]\left(1-\frac{u_0}{c}\right)^{-2}, \tag{13}$$

or

$$\tau \rightarrow 2\pi\left|1-\frac{u_0}{c}\right|\left[N^2+\rho_0^{-1}(c-u_0)\frac{d}{dz}\left(\rho_0\frac{du_0}{dz}\right)\right]^{-1/2}. \tag{14}$$

It is important that when there is a basic flow, generally speaking, there may be internal free gravity waves with periods that exceed the period of inertial oscillations. As we can see from formula (13) this occurs when a very long wave is propagating in a direction which is opposite to the basic flow. The indicated increase is directly proportional to the ratio of the velocity of the basic flow to the velocity of the internal wave.

All of the considerations outlined above refer to a neutrally stable internal wave ($c$ is a real quantity). Consideration of the possible dynamic instability of internal oscillations obviously will not lead to theoretically different conclusions concerning the influence of currents on the frequency of internal oscillations, but it may considerably limit the real frequency range of existence of internal waves.

Note that direct use of the method of P. Groen to equation (9) will lead to a double inequality

$$\frac{2\pi\left|1-\frac{u_0}{c}\right|}{\sqrt{N^2+\rho_0^{-1}(c-u_0)\frac{d}{dz}\left(\rho_0\frac{du_0}{dz}\right)}}<\tau<\frac{2\pi}{l}\left|1-\frac{u_0}{c}\right|,$$

which supports the correctness of the approximations employed in deriving formulas (13) and (14).

4. The literature contains numerous mentions of the phenomenon

of a phase jump in the oscillations in natural observations of internal waves [3, 4, 11, 13]. The phase jump of internal oscillations can easily be explained if it is observed in layers where there is a density jump, inasmuch as in this case one can employ conclusions from the wave theory at the interface [7].

In a continuously stratified liquid, the existence of a phase jump in the internal oscillations, generally speaking, may be explained formally on the basis of a determination of the normal oscillations (modes) of the system. In this case, it is easy to show that the depth of occurrence of the phase jump in the excited motion does not necessarily coincide with the level of the layer of the density jump. Instead, in the case in question, the level at which the phase jump occurs may be determined accurately as a function of the mode of the internal wave. /12

It seems to us that the explanation of the phenomenon of the phase jump can also be obtained by proceeding on the basis of the theory of hydrodynamic stability of the motion of a heterogeneous fluid for the case of movement of a viscous homogeneous fluid, Tollmin [8] showed that during the transition through the critical layer there may be a phase jump in the oscillations which govern the exciting motion. The experiments of Shubauer and Skremsted have supported this finding.

For a heterogeneous ideal fluid, the shift of the horizontal velocity relative to the flow frequently causes a phase jump with passage through a critical layer. This conclusion follows from an analysis of the work of J. Miles [18, 19].

It may be assumed that the phase jump can arise for a certain mode of the internal wave at the level at which the phase velocity of a given mode is equal to the projection of the velocity of the basic flow on the direction of propagation of the wave. This assumption theoretically allows an experimental check by performing special observations which can be carried out by standard oceanographic instruments.

Note that a similar phenomenon of a phase jump at the transition across the coincidence layer occurs in the process of generation of wind waves by the wind [14].

5. In oceanographic observations it is sometimes advantageous to differentiate the transformations of the wave process by currents, i.e., to take the Doppler effect into account. In investigating the internal tidal waves, such an estimate was carried

out by V.G. Bukhteyev [1] who assumed the waves propagate along the interface between two homogeneous fluids with uniform basic movement in the entire system. These results can easily be generalized for the case of internal gravity waves of any period, propagating in an arbitrary direction in a continuously stratified inhomogeneous fluid, in which the vector of horizontal velocity of the basic flow is a derived function of the vertical coordinate.

Then the distortion $\Delta T$ of the period of the internal wave (the difference between the observed $T_1$ and the true $T_2$ periods) may be found from the equation

$$\Delta T = T_2\left(\left|\frac{c}{c-\bar{u}}\right|-1\right). \tag{15}$$

Since in this case $\bar{u} = \bar{u}(z)$, the magnitude of the distortion of the period of internal waves is largely dependent upon the relationship between the phase velocity of the wave and the value of the projection of the velocity of basic flow in the direction of propagation of the wave. Consequently, in the general case the value of $\Delta T$ will differ at various levels of observation. /122

The Doppler effect is assumed to be taken into account in analyzing the observations that were made from a moving vessel. An appropriate procedure has been suggested by V. Kraus [5] and K. D. Sabinin [12]. However, in analyzing the observations of internal waves, performed from aboard an anchored vessel or by means of instruments mounted on automatic buoy stations, the Doppler effect usually is not taken into account. However, it must be kept in mind that the spectra of the internal waves which are obtained may be severely distorted because the velocity of the ocean currents at the horizon of the observations is not equal to zero.

If the performance of natural observations of internal waves is organized so that it is possible to calculate the phase velocity of the wave, the direction of its propagation, and also the velocity and direction of the non-periodic currents, then according to (15), the true period of the wave can be determined by the formula

$$T_2 = T_1\left|1-\frac{\bar{u}}{c}\right|.$$

In conclusion, it should be pointed out that the "observer" Doppler effect and the change in frequency (which we discussed in points 1 and 3), physically produced by marine currents, generally speaking, are identical. It is assumed in particular that the resonance phenomena in the ocean occur at frequencies that are modified by the presence of a basic flow.

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# THE PROBLEM OF CALCULATING CLOUD COVER IN CALCULATIONS OF LONG WAVE RADIATIONAL CHARACTERISTICS OF THE ATMOSPHERE

/124

Z. P. Galakhov

In conjunction with the problem of the consideration of nonadiabatic influxes of heat in numerical systems of weather forecasting, consideration of cloud cover in the calculations of radiational characteristics of the atmosphere continue to have great significance [7]. Recently, a number of studies have been carried out in this respect [1, 2, 9], in which the influence of cloud cover at various levels on radiation characteristics is explained and the accuracy of the calculation of these characteristics is evaluated in conjunction with the artificial displacement along the vertical of cloud layers on different levels.

Inasmuch as this problem is in a stage of development and any attempt to clarify it can only be of help for the general solution, this article will deal with one possible way of taking into account the cloud cover for the purpose of using it in calculating various long wave radiation characteristics at several levels in the real atmosphere.

To determine the number of clouds at middle and upper levels on the basis of available data on general and low cloud cover, the present paper will use the principle of proportionality [2, 10].

We will assume that the ratio of the apparent number of clouds at middle and upper levels is [9]:

$$\frac{n_m}{n_u} = \frac{0.6}{0.4}. \tag{1}$$

This assumption does not contradict reality: In the normal situation, one can observe a rather large number of clouds at middle and upper levels (approximately 4-6 on the scale). Therefore, the assumed proportion for the visible number must be considered most probable.

Let us assume that the total visible number of clouds (N) is the sum of the visible number of clouds in the lower ($n_l$), middle ($n_m$) and upper ($n_u$) levels:

$$N = n_l + n_m + n_u. \tag{2}$$

From expressions (1) and (2) we will have /125

$$N_m = 0.6(N - n_l); \tag{3}$$

$$N_u = 0.4(N - n_l). \tag{4}$$

To determine the actual number of clouds (with their positions on the scale being represented by analogy using $\bar{n}_l$, $\bar{n}_m$, $\bar{n}_u$), with the condition that the clouds in the higher layers are obscured by the clouds in the lower layers, we can use the relationships

$$\left.\begin{aligned} \bar{n}_l &= n_l; \\ \bar{n}_m &= \frac{n_m}{1 - n_l} \\ \bar{n}_u &= \frac{n_u}{1 - (n_l + n_m)}. \end{aligned}\right\} \tag{5}$$

From the above, taking (3) and (4) into account, we will have

$$\left.\begin{aligned} \bar{n}_l &= n_l; \\ \bar{n}_m &= \frac{0.6\ (N - n_l)}{1 - n_l}; \\ \bar{n}_u &= \frac{0.4(N - n_l)}{1 - 0.6N - 0.4n_l}, \end{aligned}\right\} \tag{6}$$

if $n_l < 1$, and

$$\left.\begin{aligned} \bar{n}_m &= 0.6; \\ \bar{n}_u &= 0.4, \end{aligned}\right| \tag{7}$$

if $n_l = 1$.[1]

The diagram of a cloud model of the atmosphere is shown in Figure 1.

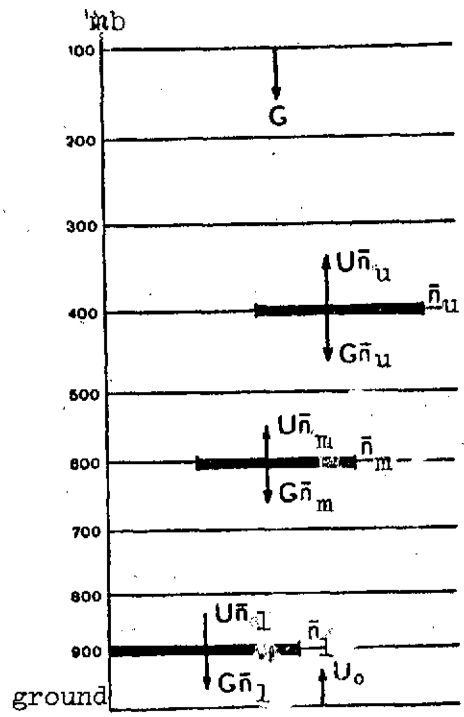


Figure 1. Diagram of a cloud model of the atmosphere. $U_0$ is the ascending radiation from the ground; G is the descending radiation from the atmosphere; $U\bar{n}_l$, $U\bar{n}_m$, $U\bar{n}_u$, represent the ascending and $G\bar{n}_l$, $G\bar{n}_m$, $G\bar{n}_u$ represent the descending long wave radiation from the clouds in the lower, middle, and upper layers, respectively.

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[1]Here and in the following the number of clouds will be expressed in fractions of one.

For convenience in the calculations, and also due to the lack of precise data on the altitudes of the upper and lower limits of the clouds in the model, the cloud layers were reduced to a film and considered to be located at levels of 900, 600, and 400 mb, which is supported by average data on the altitudes at which the lower, middle and upper layers occur, respectively [6]. On the other hand, it is mentioned in [2] that artificial displacement of clouds from the lower level along the vertical within 500 meter limits and clouds in the middle level within the limits of 1 to 1.5 kilometers introduces an error on the order of 15% in the calculations, which is within the limits of accuracy of calculation of the radiant energy fluxes.

Calculation of radiation at any level in the atmosphere under /126 cloudy conditions essentially boils down to finding the total radiation which travels from the subjacent surface and from the atmosphere in a cloudless interval and the radiation that reaches this level from the clouds on various levels, with consideration of their coverage.

Let us determine the cloudless interval Δ in the presence of (for example), three-layer cloud cover:

$$\Delta = 1 - (n_l + n_m + n_u). \tag{8}$$

Substituting from (5) the apparent number of clouds in reality, we will have

$$\Delta = 1 - [\bar{n}_l + (1 - \bar{n}_l)\bar{n}_m + \bar{n}_u(1 - \bar{n}_l) + \bar{n}_m(1 - \bar{n}_l)]. \tag{9}$$

We transform equation (9)

$$\Delta = (1 - \bar{n}_l)(1 - \bar{n}_m)(1 - \bar{n}_u). \tag{10}$$

For a two-layer cloud cover, expression (10) is simplified as follows

$$\Delta = (1 - \bar{n}_1)(1 - \bar{n}_m). \tag{11}$$

Let us find that part of the clouds on the lower level whose radiation travels up to a certain level that is located above the middle and upper clouds. To do this it is necessary to take into account the coverage of the clouds on the lower level by the clouds on the middle and upper levels. The desired portion of the cloud cover in the lower level is written in the form

$$\Delta p = \bar{n}_1 (1 - \bar{n}_m)(1 - \bar{n}_u). \tag{12}$$

By analogy, in calculating the radiation at any level, it is possible to determine both the cloudless intervals and the portions of the clouds on various levels whose radiation reaches the level where radiation fluxes are calculated.

Let us examine the case of an ascending flux. Taking into account the above and applying the principle of proportionality, we obtain the total fluxes at the following levels (in millibars):

$$\left.\begin{matrix} 800 \\ 700 \\ 600 \end{matrix}\right\} U_0 (1 - \bar{n}_1) + U\bar{n}_1;$$

$$\left.\begin{matrix} 500 \\ 400 \end{matrix}\right\} U_0 (1 - \bar{n}_1)(1 - \bar{n}_m) + U\bar{n}_1 (1 - \bar{n}_m);$$

$$\left.\begin{matrix} 300 \\ 200 \\ 100 \end{matrix}\right\} \begin{matrix} U_0 (1 - \bar{n}_1)(1 - \bar{n}_m)(1 - \delta\bar{n}_u) + U\bar{n}_1 (1 - \bar{n}_p) \cdot (1 - \delta\bar{n}_u) + \\ + U\bar{n}_m (1 - \delta\bar{n}_u) + \delta U\bar{n}_u \end{matrix} \tag{13}$$

In the case of descending radiation, by analogy we will have at these levels /127

$$\left.\begin{matrix}500\\600\end{matrix}\right\} G(1-\delta\bar{n}_u)+\delta G\bar{n}_u; \qquad (14)$$

$$\left.\begin{matrix}700\\800\\900\end{matrix}\right\} G(1-\delta\bar{n}_u)(1-\bar{n}_m)+\delta G\bar{n}_u(1-\bar{n}_m)+G\bar{n}_m;$$

and at ground level $G(1-\delta\bar{n}_u)(1-\bar{n}_m)(1-\bar{n}_1)+\delta G\bar{n}_u(1-\bar{n}_m)\cdot(1-\bar{n}_1)+$
$+G\bar{n}_m(1-\bar{n}_1)+G\bar{n}_1,$

where $\Delta$ = 0.5 is the coefficient of grayness [9].

Equally important is the solution of the problem of the radiational and absorptive capacity of the atmosphere and the clouds at various levels. However, in all of the recent studies the radiation of the atmosphere as well as the clouds in the lower and middle levels has been considered to be absolutely black, and for clouds in the upper level the coefficient of greyness is used [2, 8, 9].

This system for taking cloud cover into account for the purpose of determining the degree of its adaptability was used in the well-known method of calculating long wave radiation characteristics of the atmosphere.

As the original data for calculations, the following equations were employed, given in [2, 3, 5, 9].

$$U(z)=E(T_n)P(\mu)+\int_0^z E(T)\,dP(\mu); \qquad (15)$$

$$G(z)=-\int_0^z E(T)\,dP(\mu); \qquad (16)$$

$$\mu_{i,\,H_2O}=0{,}01\left(\frac{e_{i-1}}{P_{i-1}^{0,5}}+\frac{e_i}{P_i^{0,5}}\right)(P_{i-1}-P_i); \qquad (17)$$

$$\mu_{i,\,CO_2}=0{,}552\cdot10^{-3}(P_{i-1}^{1,8}-P_i^{1,8}); \qquad (18)$$

$$e_i=6{,}1\cdot10^{\frac{7,45\tau_i}{235+\tau_i}}, \qquad (19)$$

where $U(z)$, $G(z)$ are the ascending and descending long wave fluxes at the z level, respectively;

$E(T_n)=\sigma T_n^4$ is the radiation of an absolutely black body at a temperature $T_n$ ($T_n$ represents the temperature of the subjacent surface, cloud films and levels);

$\sigma = 0.826 \cdot 10^{-10}$ calories per $cm^2 \cdot$min$\cdot$degree$^4$--the Stefan-Boltzmann constant;

$P(\mu)$ is the integral function of transmission (taken from the data of K. Ya. Kondrat'yev and Kh. Yu. Niylisk [5]);

$\mu_{i, H_2O}, \mu_{i, CO_2}$ is the effective mass of water vapor and carbon dioxide in the i-th layer of the atmosphere in centimeters of the reduced layer; /128

$e_i$ is the water vapor tension in the i-th layer, mb;

$\tau_i$ is the dew point at the i-th level;

$P_i$ is the pressure at the i-th level, mb.

Calculation of the number of clouds is performed according to formulas (6). The calculations used a nine-layer model of the atmosphere (see Figure 1), in which the 100 millibar level was used as the upper limit. Integration of equations (15) and (16) was carried out by the method of trapezoids. The original data for the calculations consisted of many years worth of monthly temperature values, dew points at basic isobaric surfaces and new data on general and lower cloud cover [6]. These calculations were performed

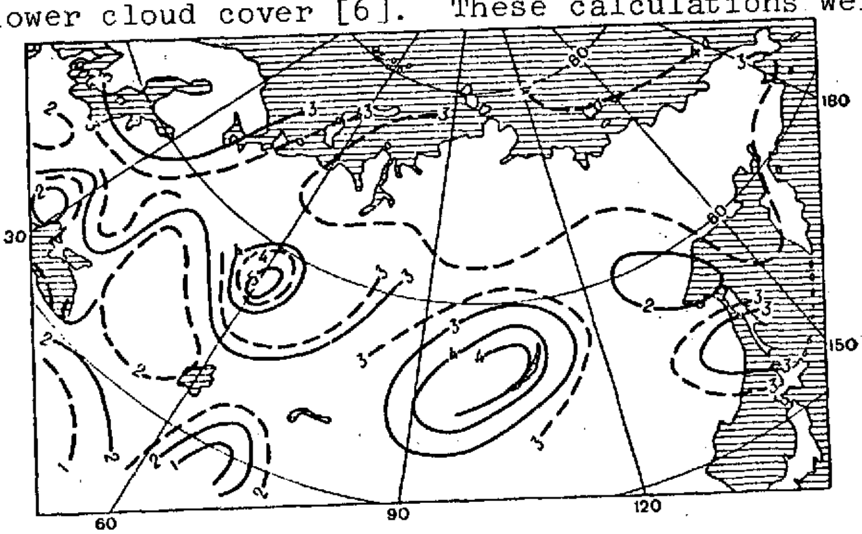


Figure 2. Average calculated (--------) and experimental (________) numbers of clouds (on a scale of values) in the 3-5 kilometer layer ($\bar{n}_{av}$).

during the central months of the various seasons for the territory of the USSR at 91 points. As a result, it was possible to obtain the number of clouds in the upper and middle layers as well as various radiational characteristics (ascending and descending long wave fluxes at these levels).

It is interesting to compare the calculated and experimental data on the amounts of clouds at middle levels. Figure 2 shows the average number of clouds on a scale of values in the 3-5 kilometer layer (middle level), determined by means of aircraft sounding, and calculated data on the number of clouds on the middle level. As we can see from the figure, these data show satisfactory agreement with each other.

Figure 3 compares the calculated and averaged (for the period from 1 to 15 July 1966) satellite data on the outgoing radiation [11] over the territory of the USSR. It should be pointed out that the average cloud situation in July coincided with the situation for cloud cover during the period from 1 to 15 July 1966. The differences that exist can be explained by the fact that the calculation was carried out on the basis of average data for many years on temperature, dew point and cloud cover, and the averaging of the satellite data was performed for a specific, incomplete month. /129

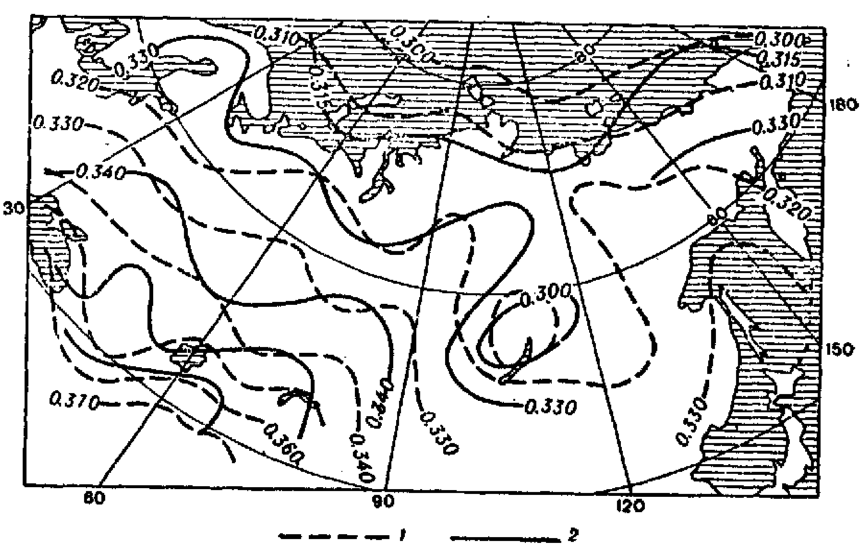


Figure 3. Calculated (1) and averaged (2) satellite data on outgoing radiation, calories per $cm^2 \cdot min$.

Obviously, this system for determining the cloud cover is far from complete, but its testing has resulted in a number of positive findings and in particular a coincidence of experimental and calculated amounts of cloud cover at middle levels, as well as the values for the radiation fluxes at the upper limit of the atmosphere.

Hence, the proposed system may be recommended for use in calculating long wave radiation characteristics of the atmosphere.

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# RECONSTRUCTING THE VERTICAL PROFILE OF HUMIDITY ON THE BASIS OF THE VERTICAL PROFILE OF TEMPERATURE

T. I. Bazlova

In temperature sounding of the atmosphere by the method of thermal location in the absorption bands for carbon dioxide and molecular oxygen, it is necessary to take into account the attenuation of radiation by water vapor. Data obtained from radiosondes indicate that the vertical temperature and humidity profiles in the atmosphere are closely linked to one another.

On the basis of the general features of the distribution of water vapor in the atmosphere, an empirical formula was proposed linking the change in humidity with the change in temperature and altitude [2]

$$\rho_{v_2}=\rho_{v_1}\exp\left[\alpha(t_2-t_1)-\beta(z_2-z_1)\right], \quad (1)$$

where $\rho_{v_2}$ and $\rho_{v_1}$ are the density of water vapor at levels $z_2$ and $z_1$;
$t_2$ and $t_1$ represent the air temperature at these same levels;
$\alpha$ and $\beta$ are the variable coefficients.

Let us examine briefly how this formula was obtained.

The density of water vapor is determined from the following relationships

$$\rho_v=\frac{e_v}{R_vT}=\frac{fE}{R_vT}, \quad (2)$$

where $e_v$ is the water vapor tension;
$R_v$ is the gas constant;
$T$ is the temperature degrees Kelvin;
$f$ is the relative humidity; and
$E$ is the maximum water vapor tension, saturated with respect to water (the film hygrometer reacts to the liquid phase of water [3]).

According to the Magnus formula [4]

$$E = E_0 \cdot 10^{\frac{at}{b+t}}, \tag{3}$$

where $E_0$ = 6.1078 mb, /132
$a^0$ = 7.63° $deg^{-1}$ and
b = 241.9°.
t is the temperature in °C.

Substituting expression (3) in (2), we will obtain

$$\rho_v = \frac{fE_0}{R_n T} \cdot 10^{\frac{at}{b+t}}. \tag{4}$$

Let us determine the change in the density of water vapor between two levels

$$\frac{\rho_{v_2}}{\rho_{v_1}} = \frac{f_2}{f_1} \cdot \frac{T_1}{T_2} \exp\left[\frac{ab \ln 10 (t_2 - t_1)}{(b + t_1)(b + t_2)}\right]. \tag{5}$$

Let us establish the relationship between the density of water vapor and the temperature in the form of an exponent

$$\frac{\rho_{v_2}}{\rho_{v_1}} \sim \exp \alpha_1 (t_2 - t_1), \quad \alpha_1 = \frac{ab \ln 10}{(b + t_1)(b + t_2)}. \tag{6}$$

The results of the calculations of the coefficient $\alpha_1$ are shown below:

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| $t_1$, °C ......... | 0 | −10 | −20 | −30 | 0 | −20 | −20 |
| $t_2$, °C ......... | 0 | −10 | −20 | −30 | −50 | −50 | −70 |
| $\alpha_1$ .......... | 0.072 | 0.079 | 0.086 | 0.094 | 0.092 | 0.100 | 0.111 |

As we can see $\alpha_1$ rises as the temperature decreases in the layer in question.

The relative humidity decreases as the temperature rises and increases when temperature falls. In an inversion layer the temperature increases, forms a stabilizing layer beneath which moisture accumulates, cloudiness develops, etc., while above the cloud layer the relative humidity decreases rapidly so that on the average the general tendency for it to decrease with increasing temperature is retained:

$$\frac{f_2}{f_1} \sim \exp\left[-\alpha_2 (t_2 - t_1)\right]. \tag{7}$$

The relative humidity has a general tendency to decrease with altitude:

$$\frac{f_2}{f_1} \sim \exp\left[-\beta (z_2 - z_1)\right]. \tag{8}$$

Substituting equations (6), (7) and (8) in (5) and taking into account that $\frac{T_1}{T_2}$ is close to unity, we will have

$$\frac{\rho_{v2}}{\rho_{v1}} = \exp\left[(\alpha_1 - \alpha_2)(t_2 - t_1) - \beta (z_2 - z_1)\right]. \tag{9}$$

Letting $\alpha_1 - \alpha_2 = \alpha$, we will obtain formula (1). The values of the coefficients $\alpha$ and $\beta$ are determined on the basis of radiosonde data by means of the method of least squares. /133

$$\alpha = \frac{\sum\limits_{i=1}^{r} \ln\left(\frac{\rho_{v2i}}{\rho_{v1i}}\right) \sum\limits_{i=1}^{r} (t_{2i} - t_{1i}) - r \sum\limits_{i=1}^{r} (t_{2i} - t_{1i}) \ln\left(\frac{\rho_{v2i}}{\rho_{v1i}}\right)}{\left[\sum\limits_{i=1}^{r} (t_{2i} - t_{1i})\right]^2 - r \sum\limits_{i=1}^{r} (t_{2i} - t_{1i})^2}; \tag{10}$$

$$\beta = \frac{\sum_{i=1}^{r} \ln\left(\frac{\rho_{v2i}}{\rho_{v1i}}\right) \sum_{i=1}^{r} (t_{2i} - t_{1i})^2 - \sum_{i=1}^{r} (t_{2i} - t_{1i}) \ln\left(\frac{\rho_{v2i}}{\rho_{v1i}}\right) \sum_{i=1}^{r} (t_{2i} - t_{1i})}{(z_2 - z_1)\left\{\left[\sum_{i=1}^{r} (t_{2i} - t_{1i})\right]^2 - r \sum_{i=1}^{r} (t_{2i} - t_{1i})^2\right\}}, \qquad (11)$$

where $r$ is the number of soundings.

At the present time, radiosonde data on humidity can be used reliably only up to an altitude of 5-6 kilometers. Above this, the data from film hygrometers are unreliable because there is an increase in inertia and a decrease in sensitivity of the humidity sensors at low humidity levels and low temperatures. Measurements of humidity in the stratosphere by means of spectral methods and condensation hygrometers 1.5-9 indicate that the stratosphere is much dryer than would be indicated from radiosonde data. The specific humidity at altitudes of 10-30 kilometers is $2 \cdot 10^{-6}$ to $15 \cdot 10^{-6}$ g/g.

Inasmuch as the conditions for formation of the humidity profile in the lower inversion layer and the upper troposphere are different, we have established three layers of the atmosphere: 0-1, 1-5 and 5-27 kilometers.

Tables 1 and 2 show the values of the coefficients $\alpha$ and $\beta$ for the first two layers on the basis of radiosonde data. Table 3 gives the values of $\alpha$ and $\beta$ for the third layer: in the first case, the actual value of the specific humidity at the 16 kilometer level is used while in the second the specific humidity at the 16 kilometer level is assumed to be $5 \cdot 10^{-6}$ g/g.

Formula (1) contains three unknown parameters: coefficients $\alpha$ and $\beta$ and the density of water vapor $\rho_{v_1}$ at the lower level $z_1$. The coefficients $\alpha$ and $\beta$ are determined on the basis of statistical data while $\rho_{v_1}$ is determined on the basis of boundary conditions. Using formula (1) we can solve two problems.

1. Determination of the vertical humidity profile if we know the vertical temperature profile and the relative humidity on the ground (observation from below)

$$\rho_{v_0} = \frac{f_0 E_0}{R_n T_0} \cdot 10^{\left(\frac{a t_0}{b + t_0} - 2\right)}; \qquad (12)$$

$$\rho_{v1} = \rho_{v0} \exp\left[\alpha (t_1 - t_0) - \beta (z_1 - z_0)\right]. \tag{13}$$

For any intermediate level

$$\rho_{vi} = \rho_{v(i-1)} \exp\left[\alpha \left(t_i - t_{i-1}\right) - \beta \left(z_i - z_{i-1}\right)\right]. \tag{14}$$

On the basis of the density of water vapor, the relative humidity can be determined:

$$f_i = \rho_{vi} \frac{R_n T_i \cdot 10^2}{E_0 \cdot 10^{\frac{at_i}{b+t_i}}}. \tag{15}$$

We then check to see whether $f_i$ is greater than 100%. If $f_i$ is equal to or greater than 100% then a correction is introduced in $\rho_{v_1}$

$$\rho^*_{vi} = \frac{E_0}{R_n T_i} \cdot 10^{\frac{at_i}{b+t_i}}. \tag{16}$$

The value of $\rho_{v_{(i+1)}}$ is calculated according to the corrected value of $\rho^*_{v_i}$ /135

$$\rho_{v(i+1)} = \rho^*_{vi} \exp\left[\alpha \left(t_{i+1} - t_i\right) - \beta \left(z_{i+1} - z_i\right)\right]. \tag{17}$$

TABLE 1. VALUES OF COEFFICIENTS α AND β /134

| Station | r | $z_1=0$, $z_2=1$ km | | $z_1=1$ km, $z_2=5$ km | |
|---|---|---|---|---|---|
| | | α | β | α | β |
| | | Winter (November-May) | | | |
| Kheys Island | 34 | 0.080 | 0.048 | 0.070 | 0.154 |
| Amderma | 37 | 0.073 | 0.121 | 0.063 | 0.182 |
| Cape Zhelaniya | 39 | 0.064 | 0.071 | 0.058 | 0.170 |
| Belyy Island | 38 | 0.080 | 0.037 | 0.073 | 0.122 |
| Vize Island | 48 | 0.079 | 0.038 | 0.088 | 0.066 |
| Dikson Island | 48 | 0.068 | 0.003 | 0.078 | 0.114 |
| Cape Chelyuskin | 14 | 0.072 | 0.035 | 0.034 | 0.293 |
| Tixie Bay | 38 | 0.079 | 0.014 | 0.072 | 0.116 |
| Kotel'nyy Island | 40 | 0.081 | 0.050 | 0.050 | 0.199 |
| Zhokhov Island | 24 | 0.067 | 0.044 | 0.084 | 0.076 |
| Ayon Island | 37 | 0.069 | 0.067 | 0.084 | 0.076 |
| Wrangel Island | 56 | 0.069 | 0.018 | 0.069 | 0.154 |
| SP-10, 13, 14 | 16 | 0.106 | 0.209 | 0.084 | 0.076 |
| All Stations | 469 | 0.076 | 0.039 | 0.072 | 0.127 |
| | | Summer (June-October) | | | |
| Kheys Island | 28 | 0.002 | 0.265 | 0.062 | 0.166 |
| Amderma | 40 | 0.044 | 0.132 | 0.018 | 0.436 |
| Cape Zhelaniya | 32 | 0.032 | 0.172 | 0.077 | 0.069 |
| Belyy Island | 43 | 0.049 | 0.149 | 0.048 | 0.242 |
| Vize Island | 41 | 0.037 | 0.154 | 0.024 | 0.598 |
| Dikson Island | 41 | 0.052 | 0.117 | 0.076 | 0.108 |
| Cape Chelyuskin | 20 | 0.029 | 0.293 | 0.082 | 0.044 |
| Tixie Bay | 28 | 0.018 | 0.269 | 0.006 | 0.518 |
| Kotel'nyy Island | 32 | 0.040 | 0.197 | 0.091 | 0.043 |
| Zhokhov Island | 18 | 0.022 | 0.278 | 0.016 | 0.448 |
| Ayon Island | 63 | 0.033 | 0.210 | 0.021 | 0.361 |
| Wrangel Island | 40 | 0.026 | 0.200 | 0.054 | 0.185 |
| SP-10, 13, 14 | 18 | 0.041 | 0.288 | 0.068 | 0.125 |
| All Stations | 444 | 0.034 | 0.194 | 0.037 | 0.289 |

## TABLE 2. VALUES OF COEFFICIENTS α AND β

| Station | r | $z_1$=5km, $z_2$=16 km, $q_{16}$ actual | | r | $z_1$=5 km, $z_2$=16 km, $q_{16}=5\cdot10^{-6}$ g/g | |
|---|---|---|---|---|---|---|
| | | α | β | | α | β |
| | | Winter (November-May) | | | | |
| Kheys Island | 34 | 0.091 | 0.058 | 34 | 0.015 | 0.448 |
| Amderma | -- | -- | -- | 37 | 0.024 | 0.448 |
| Cape Zhelaniya | 39 | 0.091 | 0.060 | 39 | 0.016 | 0.455 |
| Belyy Island | -- | -- | -- | 38 | 0.030 | 0.432 |
| Vize Island | -- | -- | -- | 48 | 0.017 | 0.451 |
| Dikson Island | 48 | 0.092 | 0.058 | 48 | 0.008 | 0.455 |
| Cape Chelyuskin | 14 | 0.087 | 0.065 | 14 | 0.016 | 0.516 |
| Tixie Bay | 38 | 0.088 | 0.061 | 38 | 0.007 | 0.473 |
| Kotel'nyy Island | 40 | 0.092 | 0.053 | 40 | 0.010 | 0.471 |
| Zhokhov Island | 24 | 0.082 | 0.056 | 24 | 0.028 | 0.449 |
| Ayon Island | -- | -- | -- | 37 | 0.050 | 0.427 |
| Wrangel Island | 55 | 0.079 | 0.073 | 56 | 0.032 | 0.438 |
| SP-10, 13, 14 | 10 | 0.102 | 0.054 | 16 | 0.008 | 0.459 |
| All Stations | 375 | 0.091 | 0.057 | 469 | 0.018 | 0.453 |
| | | Summer (June-October) | | | | |
| Kheys Island | 28 | 0.066 | 0.113 | 28 | 0.028 | 0.526 |
| Amderma | 40 | 0.067 | 0.093 | 40 | 0.045 | 0.476 |
| Cape Zhelaniya | 32 | 0.074 | 0.089 | 32 | 0.056 | 0.473 |
| Belyy Island | 43 | 0.062 | 0.125 | 43 | 0.041 | 0.496 |
| Vize Island | 40 | 0.055 | 0.138 | 41 | 0.049 | 0.472 |
| Dikson Island | 20 | 0.064 | 0.113 | 20 | 0.068 | 0.430 |
| Cape Chelyuskin | 41 | 0.057 | 0.128 | 41 | 0.036 | 0.502 |
| Tixie Bay | 28 | 0.060 | 0.120 | 28 | 0.059 | 0.440 |
| Kotel'nyy Island | 32 | 0.048 | 0.132 | 32 | 0.045 | 0.469 |
| Zhokhov Island | 18 | 0.050 | 0.143 | 18 | 0.045 | 0.468 |
| Ayon Island | -- | -- | -- | 63 | 0.049 | 0.474 |
| Wrangel Island | 41 | 0.046 | 0.156 | 41 | 0.036 | 0.503 |
| SP-10, 13, 14 | 18 | 0.101 | 0.215 | 18 | 0.010 | 0.539 |
| All Stations | 428 | 0.058 | 0.125 | 444 | 0.044 | 0.483 |

2. The determination of the vertical humidity profile on the basis of the known temperature profile and the moisture content of the atmosphere (observations from above).

Let us calculate the moisture content of the atmosphere, integrating the density of the water vapor

$$W=\int_0^H \rho dz=\sum_{j=0}^{n}\int_{z_j}^{z_{j+1}} \rho_j \exp\left[\alpha(t-t_j)-\beta(z-z_j)\right] dz. \tag{18}$$

We will assume that the temperature gradient in the layer from $z_j$ to $z_{j+1}$ is constant /136

$$\gamma=-\frac{t_{j+1}-t_j}{z_{j+1}-z_j}. \tag{19}$$

Then the temperature at any intermediate level will be calculated according to the formula

$$t=t_j-\gamma(z-z_j). \tag{20}$$

Substituting (20) in (18), we will have

$$\begin{aligned} W&=\sum_{j=0}^{n}\rho_j\int_{z_j}^{z_{j+1}}\exp\left[-(\alpha\gamma+\beta)(z-z_j)\right]dz= \\ &=\sum_{j=0}^{n}\rho_j\left(-\frac{1}{\alpha\gamma+\beta}\right)\{\exp\left[-(\alpha\gamma+\beta)(z_{j+1}-z_i)\right]-1\}; \end{aligned} \tag{21}$$

$$\begin{aligned} W&=\rho_0\sum_{j=0}^{n}\frac{z_{j+1}-z_j}{\alpha(t_{j+1}-t_j)-\beta(z_{j+1}-z_j)}\exp\left[\alpha(t_j-t_0)-\beta(z_j-z_0)\right]\times \\ &\times\{\exp\left[\alpha(t_{j+1}-t_j)-\beta(z_{j+1}-z_j)\right]-1\}. \end{aligned} \tag{22}$$

If in some layer $\alpha\gamma+\beta$ turns out to be equal to 0, the contribution of this layer to the total sum will be equal to

$$\rho_0 (z_{j+1} - z_j) \exp [\alpha (t_j - t_0) - \beta (z_j - z_0)]. \quad (23)$$

Formula (22) makes it possible to determine the density of water vapor at the ground on the basis of the known moisture content of the atmosphere. Further construction of the vertical humidity profile takes place according to formulas (14), (16), and (17).

Figure 1 shows the results of construction of the vertical humidity profile for Vize Island. In the calculations, the values of coefficients $\alpha$ and $\beta$ shown in Table 3 were used.

TABLE 3. VALUES OF COEFFICIENTS $\alpha$ AND $\beta$

| Layers | Winter (November-May) | | Summer (June-October) | |
|---|---|---|---|---|
| | $\alpha$ | $\beta$ | $\alpha$ | $\beta$ |
| 0-1 kilometer | 0.08 | 0.04 | 0.03 | 0.19 |
| 1-5 | 0.07 | 0.12 | 0.04 | 0.29 |
| 5-27* | 0.09 | 0.06 | 0.06 | 0.12 |
| 5-27** | 0.02 | 0.45 | 0.04 | 0.48 |

*$q_{16}$--actual

**$q_{16} = 5 \cdot 10^{-6}$ g/g

In determining the functions for transmission of the atmosphere /137
it is necessary to know the density of the water vapor, but description of the distribution of water vapor in the atmosphere most frequently makes use of the specific humidity function. Therefore, all of the graphs are plotted for the distribution of specific humidity by altitude. The transition from $\rho_v$ to q is carried out according to the formula

$$q = 0.622 \rho_v \frac{R_v T}{P}. \quad (24)$$

A comparison of the calculated profiles of humidity with the actual ones showed that the assumption of agreement of the temperature and humidity profiles was valid. Choice of coefficients $\alpha$ and $\beta$ was made on the basis of statistical data concerning the distribution of temperature and humidity in the atmosphere. Since $\alpha$ is a function of temperature and $\beta$ depends upon conditions of formation of the distribution of water vapor, division into seasons and regions must be quite clear. It is apparent from Table 2 the coefficients $\alpha$ and $\beta$ change significantly from one station to another.

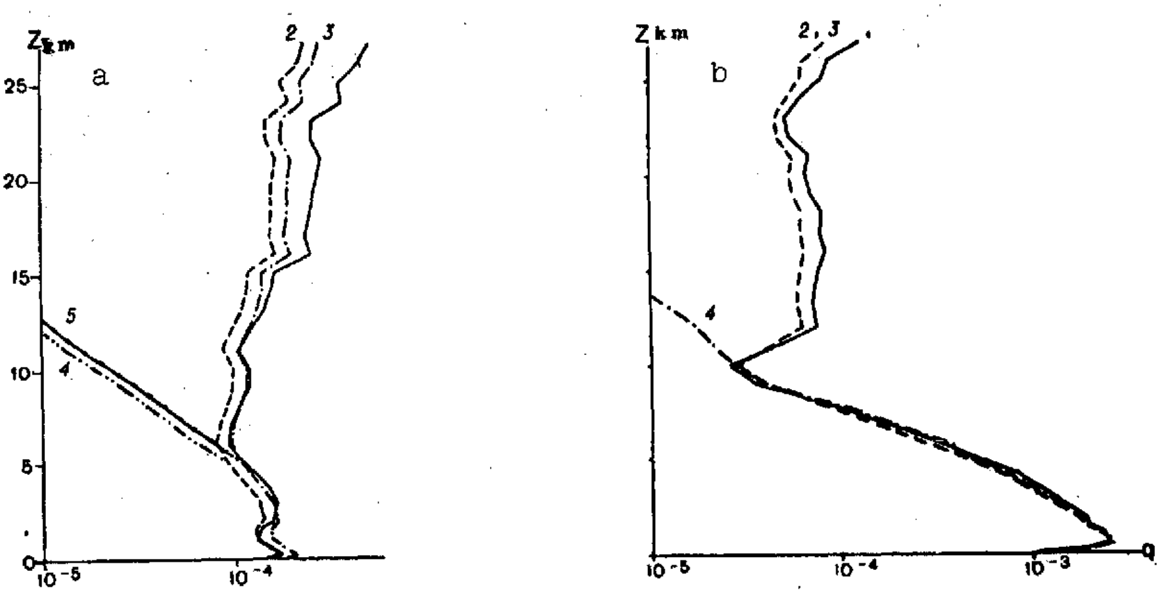


Figure 1. Distribution of specific humidity in the atmosphere: a--Probe no. 148, 25 February 1963; b--Probe no. 192, 26 November 1966. 1--actual profile of specific humidity; 2--reconstructed profile on the basis of the known humidity at the ground ($\alpha$ and $\beta$ under the condition $q_{16\ actual}$) 3--profile reconstructed according to the known moisture contact of the atmosphere ($\alpha$ and $\beta$ under the condition $q_{16\ actual}$); 4--profile reconstructed on the basis of the known humidity at the ground; 5--profile reconstructed according to the known moisture content of the atmosphere ($\alpha$ and $\beta$ under the condition $q_{16} = 5 \cdot 10^{-6}$ g/g).

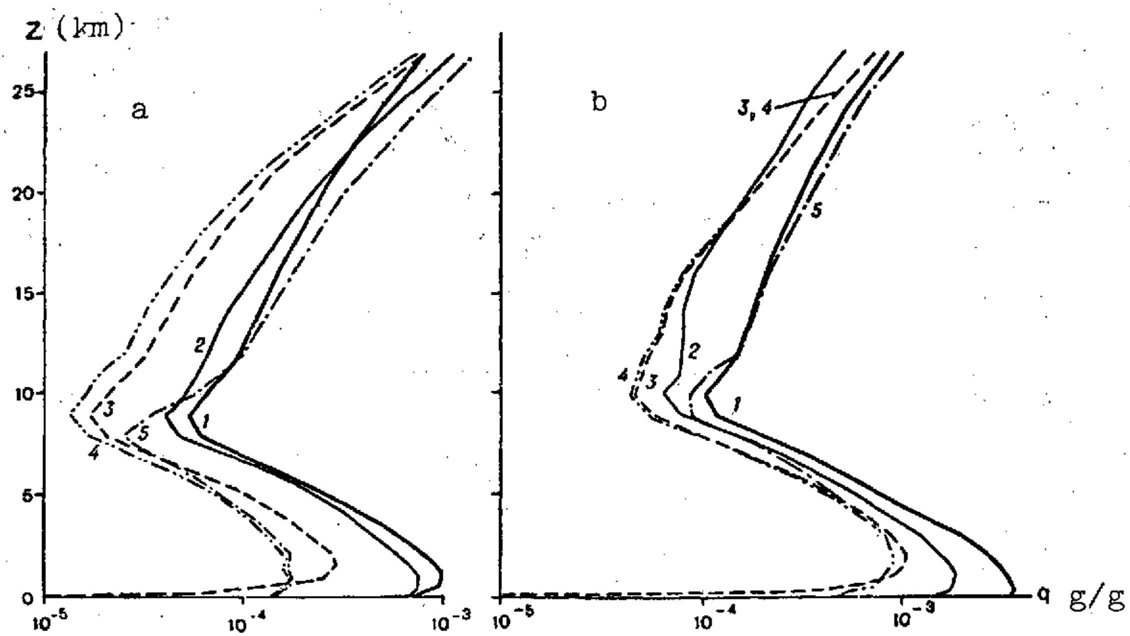


Figure 2. Mean square deviations of calculated profiles of specific humidity from the actual values for winter (a) and summer (b): 1--average profile of specific humidity; 2--mean square deviation of actual profiles from the average; 3--mean square deviations of actual profiles from the calculated values on the basis of known humidity at the ground (α and β under the condition $q_{16\ actual}$); 4--mean square deviations of actual profiles from the calculated ones on the basis of known moisture content of the atmosphere (α and β under the conditions of $q_{16\ actual}$); 5--mean square deviations of actual profiles from those calculated on the basis of a known moisture content of the atmosphere (α and β under the condition $q_{16} = 5 \cdot 10^{-6}$ g/g).

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Figures 2 a and b show the mean square deviations of the actual profiles of specific humidity from the calculated ones. These deviations are much less than the deviations of the actual profiles from the average, i.e., the calculated profiles describe the distribution of the humidity more exactly than the average profile. The exception is the layer of atmosphere above /139 18 kilometers (in summer). The data on the distribution of humidity above 16 kilometers were not used in determining the coefficients $\alpha$ and $\beta$, so that it is impossible to require coincidence of calculated data with actual data at altitudes above 16 kilometers.

For a more precise description of the distribution of humidity in the atmosphere, it is necessary to increase the number of layers in which coefficients $\alpha$ and $\beta$ are determined. For example, it is necessary to divide the layer from 5 kilometers to the tropopause, from the tropopause to 16 kilometers, and from 16 to 27 kilometers. It is better to carry out the calculations on the basis of the coefficients $\alpha$ and $\beta$, obtained for a given station, and not determined for all Arctic stations.

The humidity profiles calculated with coefficients $\alpha$ and $\beta$, calculated with the condition of a dry stratosphere ($q_{16} = 5 \cdot 10^{-6}$ g/g), differ significantly from the actual humidity profiles in the stratosphere. Obviously, film sensors increase the values of humidity, but it is impossible to assume that the stratosphere at all levels and at all seasons of the year is always dry to the same extent ($q \approx 10^{-6}$ g/g). Simultaneous sounding of the humidity in the atmosphere by several methods would be of great value: weight, spectroscopy, condensation and film sensors. This would make it possible to determine the accuracy and correction of the radiosonde data.

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## ABSTRACTS OF ARTICLES

Ye. P. Borisenkov and O. M. Fedorov. Automated System for Measurement, Collection, and Processing of Hydrometeorological Data Aboard Scientific Research Vessels of the GUGMS (SIGMA-s). (p. 1)

(Translation of "Avtomatizirovannaya sistema izmereniya sbora i obrabotki gidrometeorologicheskoy informatsii na nauchno-issledovatel'skikh sudakh GUGMS (SIGMA-s).")

The authors discuss the automated system known as SIGMA-s for the measurement, collection, and processing of hydrometeorological data aboard scientific research vessels of the Hydrometeorological Service. The various components of the system and the interfacing between them are described, as well as the projects that the system is equipped to handle.

I. A. Dyubkin. Software for the SIGMA-s. (p. 19)

(Translation of "O matematicheskom obespechenii SIGMA-s.")

The software needed for the SIGMA-s is described. Various mathematical procedures, such as introducing corrections and parameters, interpolating for depth and altitude, isolating special points and layers in the distribution of hydrometeorological elements, smoothing of signals from sensors, critical analysis of and setting up the results in graphs and tables, coding of the data into information carriers, and recording of the data, are presented.

I. A. Dyubkin and I. I. Lodkin. The Problem of Organization of a Coastal Coordinating Computer Center. (p. 34)

(Translation of "K voprosy organizatsiy beregovogo koordinatsionnovychislitel'nogo tsentre.")

The authors provide the fundamental principles of the operation of a coastal coordinating and computing center under conditions of automation. Special attention is devoted to the work of Coastal Computer Center of the Arctic and Antarctic Scientific Research Institute. This center generalizes from data collected in expeditions and also from observations made at polar stations.

I. A. Dyubkin, L. N. Klyukbin, and V. A. Romantsov. A System of Automated Processing of Deep Water Hydrological Information. (p. 49)

(Translation of "Sistema avtomatizirovannoy obrabotki glubokovodnoy gidrologicheskoy informatsii.")

An automated system for primary and scientific analysis of deep water hydrological information is presented. Primary processing of the data in this system is carried out on a drifting station, which also calculates the parameters of vertical stability of the sea layers, as well as their depths and altitudes. Methods of processing the raw data are described.

O. S. Zudin and B. A. Nelepo. Error in Interpolation and Choice of the Range of Discreteness in Measurements in a Hydrophysical Field. (p. 71)

(Translation of "Oshibka interpolyatsii i vybor intervala diskretnosti izmereniy na gidrofizicheskom pole.")

Errors in interpolation and the choosing of the range of discreteness when making measurements in a hydrophysical field are discussed. Equations for optimum interpolating based on the theory of linear interpolation of stationary random sequences are presented; analogous equations are derived for the case of data collected at stations located at the apices of a right triangle.

V. A. Stepanyuk. The Problem of Selecting an Optimum Frequency for a Measuring Generator in Determining the Value of the Hydrophysical Parameter With a Given Accuracy. (p. 80)

(Translation of "K voprosy vybora optimal'noy chastoty izmeritel'nogo generatora pri opredelenii velichiny gidrofizicheskogo parametra s zadannoy tochnost'yu".)

The selection of the optimum frequency for a measuring generator for determining the value of the hydrophysical parameter with a given degree of accuracy is discussed. Methods from information theory for measuring generators are described. Conversion of the frequency of generators into digital form by means of statistical averaging is also described.

Ye. P. Borisenkov. Small Parametric Model of the Precomputation of Meteorological Fields on the Basis of Complete Equations and Its Energetic Analogs. (p. 85)

(Translation of "Maloparametricheskaya model' predvychislenniya meteorologicheskikh poley po polnym uravneniyam i eye energeticheskiye analogi.")

A small parametric, nonadiabatic model for precomputation of meteorological fields on the basis of complete equations, along with its energetic analogs, are described. The model incorporates integral characteristics of the components of the wind speed and the analogous functions of the total fluxes of the ocean, and uses a Cartesian isobaric system of coordinates.

A. P. Nagurnyy. Estimate of Heat Fluxes on the Subjacent Surface (According to Data From Synoptic Analysis. (p. 112)

(Translation of "Otsenka potokov tepla na podstilayushchey poverkhnosti (po dannym sinopticheskogo analiza.")

The author discusses several methods of estimating heat fluxes from nonadiabatic sources distributed over a subjacent surface. Data calculated by synoptic analysis for the entire northern hemisphere from aerological soundings at the $AT_{500}$ and $AT_{400}$ level, along with the temperature of the subjacent surfaces, were used. A polytropic model of the atmosphere is used in order to avoid the problems posed by the lack of any complete theory of heat transfer in the lower atmosphere.

Ye. P. Borisenkov. A Small-Parameter Model of Circulation in an Homogeneous Baroclinic Ocean. (p. 121)

(Translation of "Maloparametricheskaya model' tsirkulyatsii v neodnorodnom baroklinnom okeana.")

A small-parameter model of circulation in an homogeneous baroclinic ocean is presented. The principles common to the construction of small parameter models and certain energetic principles developed in connection with atmospheric processes are made use of. These principles have already been applied in the study of processes in a baroclinic ocean.

V. G. Savchenko and V. R. Fuks. The Problem of the Influence of Ocean Currents on Free Internal Gravity Waves. (p. 145)

(Translation of "K voprosy o vliyanii morskikh techeniy na svobodnyye vnutrenniye gravitatsionnyye volny.")

The influence of ocean currents on free internal gravity waves is discussed. The dependence of the parameters of gravity waves on the characteristics of stationary marine currents is described. The necessary conditions for existence of these waves are obtained, and the phenomenon of abrubt changes in phase of the internal oscillation with depth is explained.

V. P. Galakhov. The Problem of Calculating Cloud Cover in Calculations of Long Wave Radiational Characteristics of the Atmosphere. (p. 159)

(Translation of "K voprosy ycheta oblastnosti pri raschetakh dlinnovolnovykh radiatsionnykh kharakteristik atmosfery.")

This article describes the results of calculating the fluxes of outgoing long wave radiation, taking cloud cover into account, on the basis of mean monthly data. A three-level and a nine-level model of the atmosphere is used, the latter with a one-hundred millibar level as upper limit. Data used in the calculations had been collected over many years.

T. I. Bazlova. Reconstructing the Vertical Profile of Humidity on the Basis of the Vertical Profile of Temperature. (p. 169)

(Translation of "Vosstanovleniye vertikal'nogo profilya vlazhnosti po vertikal'nomi profilyu temperatury.")

The vertical profile of humidity in the atmosphere is developed on the basis of the vertical profile of temperature using an empirical formula linking changes in humidity with changes in temperature and altitude. The atmosphere is devided into three layers by altitude, since the conditions for the formation of humidity varies with altitude.

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